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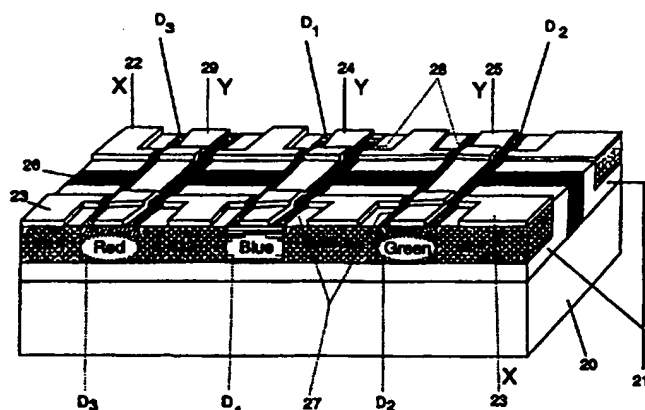
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(54) Title: MONOLITHIC LIGHT EMITTING DIODE ARRAYS AND DISPLAY ASSEMBLIES BASED THEREON



(57) Abstract

Monolithic semiconductor light emitting diode (LED) array which is in particular suited for use as basic building block of an LED display or multicolor lamp for illumination of a light modulating display panel. The present array comprises a substrate (20) and a semiconducting layer (21) situated thereon in which two or more metal-insulator or p-i-n type LEDs are formed. The first of said LEDs has a first active region (D<sub>1</sub>) which is compensated by a first group of impurities and has a first metal Schottky contact (24). Said LED further comprises a first conductive region (23.2) which has a first ohmic contact and is situated adjacent to said first active region (D<sub>1</sub>). The second LED comprises a second active region (D<sub>2</sub>) which is compensated by a second group of impurities and has a second metal Schottky contact (25), and a conductive region (23.3) which has a second ohmic contact and is situated adjacent to said second active region (D<sub>2</sub>). The active regions (D<sub>1</sub>, D<sub>2</sub>) of these two LEDs are formed by means of laterally varied impurity introduction into the semiconducting layer (21) such that - if a bias is applied between said ohmic metal contacts and Schottky contacts - electrical charges are injected from said ohmic metal contacts into said conductive regions. From there the charges are transported primarily parallel to the substrate plane into said first or second active regions where they lead to impurity-induced multicolor electroluminescence.

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**DESCRIPTION****Monolithic Light Emitting Diode Arrays and  
Display Assemblies Based Thereon****TECHNICAL FIELD**

10 The present invention concerns monolithic semiconductor light emitting diode arrays which are well suited as building blocks of an LED display, or as lamps for illumination of light modulating display panels such as liquid crystal display (LCD) or digital micromirror display (DMD). It further concerns improved frame-sequential display assemblies enabled by these  
15 semiconductor lamps.

**BACKGROUND OF THE INVENTION**

Displays have an important function as human interfaces for making  
20 information available through visualization. We herein concentrate on LED displays and displays that comprise a light source and a light modulating display panel having a plurality of pixels that can be individually addressed and switched. Light modulating displays commonly function in the transmissive mode where the lamp and image are on opposite sides of the  
25 display plane. The image is generated from those pixels driven into a transmissive state. By individually activating each pixel in sequence, i.e. by switching them from the non-transmissive state to the transmissive state, whole images are composed for viewing. Each pixel of such a display panel functions as a light valve. They are non-emissive, rather they form images  
30 and characters by modulating the intensity of a backlight.

A second kind of display forms the image on the same side of the display plane as the lamp. The image is generated by those pixels driven into a

1 reflective state, whereas all non-active pixels absorb, transmit or otherwise  
redirect the light away from the viewer. Transmissive and reflective  
displays will hereinafter be referred to as light modulating displays or light  
modulators.

5 For monochrome displays, only a bright light source is needed to generate  
a visible image. Color displays are more complex and therefore expensive  
because they must provide several colors and mixtures thereof. Full color  
displays based on light modulators have usually red, green, and blue color  
10 filters, each aligned with a so-called subpixel in the display panel, in  
conjunction with a 'white' lamp. Three adjacent subpixels form one pixel,  
and therefore require three times the driver circuitry as does monochrome  
for the same resolution. Nevertheless, the consumer demands color.

15 Different display panel technologies modulate a lamp to form images.  
Examples are LCD panels, digital mirror device displays, electrochromic  
displays, and displays utilizing light transmitting ceramics such as PLZT,  
just to name some.

20 The resolution of a given size display is defined by the pixel density, and is  
limited by the minimum attainable pixel size. Typical LCD pixels today are  
 $100\mu\text{m} \times 100\mu\text{m}$  while DMD achieves  $20\mu\text{m} \times 20\mu\text{m}$ . Smaller pixel sizes  
are desirable because they improve image quality and increase the number  
of display panels manufacturable from a fixed substrate size.

25 Each pixel must be individually addressable. This is accomplished by  
arranging the pixels into an x-y matrix in which each pixel has a unique x,y  
coordinate. The image data are input sequentially by activating single  
y-address lines and simultaneously feeding the image level down the  
30 column in parallel through the x-address lines.

An LCD pixel is controlled by an external drive voltage applied to the pixel  
electrode. The voltage locally modifies the optical properties of the liquid

1 crystal which in turn modulates polarized light incident on the pixel. An  
image is compiled from the sum of the contributions of the sequentially  
addressed pixels.

5 Digital Micromirror displays (DMDs) consist of a large number (0.5-2.0  
million) of individual, mechanically hinged mirrors fabricated on top of, and  
integrated with a silicon static random access memory (SRAM) chip.  
Through electrostatic forces supplied by the SRAM cells, the hinged mirrors  
can individually be rotated by +10 or -10 degrees from horizontal.  
10 Collimated light incident on the DMD is modulated by separation upon  
reflection from the mirrors in either state. An image composed of one beam  
is then projected by an optical system to a screen. An introduction to this  
technology, which was developed by Texas Instruments, is given in the  
article "Displays for HDTV: Direct-View CRT's and Projection Systems",  
15 I. Gorog, Proceedings of the IEEE, Vol. 82, No. 4, April 1994, pp. 520 - 536,  
for example.

Two addressing schemes are prevalent: passive matrix (PM) and active  
matrix (AM). In the PM scheme, the information is delivered to the pixel via  
20 the address lines for the duration of one address cycle. In the following  
cycle, when the next column is addressed, there is no longer any signal  
being applied to the previous column. PM is inexpensive, because only  
address lines must be fabricated, but low performance. High viscosity liquid  
crystals preserve the pixel information after the drive voltage is removed  
25 but the necessarily slow response time rules out video display rates.  
Furthermore, pixel density is limited by address line crosstalk arising from  
the need to transport the full drive current over the address lines.

The AM scheme relies on a non-linear device situated at each subpixel,  
30 most commonly a thin film transistor (TFT), to amplify and maintain the  
address signal beyond the cycle duration. Faster liquid crystals can be used  
to attain video display rates since the AM device maintains constant pixel  
drive voltage until the image is next refreshed. The TFT action suppresses

1 crosstalk by permitting a small voltage transported over the address lines to  
control a larger voltage applied at the pixel electrode, and through their  
threshold voltage which makes off-state TFTs insensitive to small voltage  
fluctuations.

5 As LCD pixels become smaller, they become less efficient. The address  
lines and AM consume a larger fraction of the display real estate while  
pixels themselves become less transmissive or reflective. In terms of  
efficiency, color LCDs are at a disadvantage to monochrome because the  
10 requirement of subpixels dictates that a color display of the same size and  
resolution have light valves only one third of the size. Furthermore, the use  
of color filters causes 2/3 of the incident light to be absorbed before it can  
even be put to use. It is therefore highly desirable to develop a full color  
display technology which can achieve this function without the use of  
15 subpixels.

All light modulating color display schemes, both transmissive and reflective,  
must address the problem of separating a full color gamut light source into  
individual colors which can be modulated at the pixel or subpixel level. The  
20 widest color gamut requires the presence of the three primary colors: red,  
green, blue, and we focus our discussion on this example. However, the  
discussion applies to any arbitrary superposition of colors.

The most prevalent schemes for processing the separate color components  
25 of a display image are spatial sequential color (SSC) and frame sequential  
color (FSC). SSC, which is preferred for LCDs, uses pixels composed of  
three subpixels in parallel, each of which modulates one primary color.  
Usually, this is achieved by color filters in series with each subpixel which  
permit only one color to be incident or transmitted. FSC, used in DMD for  
30 example, eliminates subpixels by illuminating every pixel with each primary  
color in sequence. Most FSC displays employ a rotating color filter wheel in  
conjunction with a 'white' light source. Such arrangements of moving parts  
can be complex and bulky. Other FSC displays use a series of color filters,

1 crossed polarizers, and polarization shifters. These are also bulky and  
expensive. Other known systems use separate strobed monochrome light  
sources. This approach can present problems owing to limited lamp life  
and/or the relatively slow color-change speeds obtainable. The three lamps  
5 used in these systems are arc lamps which need high voltage, consume a  
lot of power, are shock sensitive, and bulky. To illuminate the display panel  
evenly, lenses and other optical elements are needed for each lamp. In the  
GB patent 2172733, a display assembly is mentioned in passing, which  
comprises an array of about 400 discrete LEDs (see Figure 4a and 4b of this  
10 patent) mounted on a plate. To our knowledge, it was not possible at that  
time to make semiconductor LEDs of all three primary colors; blue LEDs  
were not available. It is a clear disadvantage of the array shown in the GB  
patent that it is bulky and expensive.

15 In SSC, the subpixels are spaced sufficiently close that the eye observes a  
continuous image, often with the aid of diffusing plates which eliminate  
residual granularity. In FSC, the color cycles are sufficiently fast that the eye  
observes the average of the three color frames. FSC eliminates the need for  
subpixels which is its fundamental advantage. A drawback of FSC is that  
20 while the color sequence is faster than the optical response time of the eye,  
the eye can move quickly enough to spatially displace successive frames on  
the retina. This undesirable phenomenon is referred to as 'color flicker'.  
FSC also requires that individual pixels be modulated at 3 times the speed  
needed for SSC. This presents a technical challenge.

25

Small area, high resolution displays are needed for both projection and  
retinal displays. For projection displays, the size and expense of the system  
optics scale directly with the display size. For retinal displays, the picture  
must be small to comfortably couple to the eye at close range and to be  
30 compact and light weight. Typical examples of retinal displays are  
camcorder viewfinders and head mounted displays (HMD). HMDs are  
increasingly important for mobile information retrieval, virtual reality  
environments and games. A cheap and comfortable HMD with good picture

1     quality will find a broad market for video based computer games and mobile  
information retrieval applications, such as an airline passenger who wishes  
to scan electronic mail while waiting in the terminal. Professionals whose  
work is facilitated by a HMD will purchase lightweight, sophisticated  
5     systems wearable over extended work periods. Examples are a  
repairperson needing on site access to bulky manuals and diagrams, or a  
surgeon needing a magnified image or the patient's vital signs who cannot  
afford to be disoriented by constantly looking up at a wall screen.

10    In all display applications, the number of pixels determines the maximum  
image quality. Sony Corp. has recently announced 100,000 monochrome  
LCD pixels on a square cm area which, with FSC, is roughly 1/3 of the pixel  
number required for the VGA television standard. Progress continues at a  
rapid pace.

15     Presently, DMD technology offers a higher pixel density. In addition, the  
DMD micromirrors can be switched very fast to permit a time modulated  
gray scale at video rates. However, LCD technology has not reached its  
limits in pixel density and operation speed. It was demonstrated, for  
20    example, that a higher switching speed can be achieved by means of a  
revolutionary driving scheme. The basic idea of the driving scheme is to  
replace the standard line-at-a-time addressing technique by addressing  
multiple rows simultaneously and selecting each row many times per frame.  
A short introduction to this approach is published in "Flat Panel Display  
25    Technology", J.P. Ziegler et al., The Electrochemical Society Interface,  
Summer 1994, pp. 27 - 32. Higher speeds will also be realized by thinner LC  
layers.

30     Optimized lamp technologies for LCDs and projection displays need to be  
developed. Especially needed are high brightness 'point' or 'line' sources  
whose light can be easily collimated for uniform illumination of the display  
panel. As with display size, the size and expense of the collimating optics  
scale directly with the point source size or line source width.

1 Arc lamps in all geometries are often preferred due to their efficiency and  
brightness. The smallest arc lamp commercially available from Philips  
Lighting has a 4.5 mm arc length, produces 50 Candela (C) of 'white' light,  
and consumes 2 W at more than 1 kV. High voltage operation is  
5 unavoidable in arc lamps because of the need to ignite a plasma discharge.  
At constant voltage, the electric field scales inversely with arc length. As a  
result, arc lamp filament sizes are severely limited by reliability problems  
arising from increasingly energetic ion bombardment of the filament. HMD  
applications only require a screen brightness of roughly 50 mC. High  
10 voltage arc lamps need bulky transformers, are inefficient at such low  
brightness and introduce safety concerns in HMD and other retinal display  
applications.

Light emitting diode (LED) displays are flat, lightweight, bright and have - In  
15 comparison with LCDs - a wide viewing angle. The LED response speed is  
10-100 ns compared with 10-100 ms for LCDs. In addition, LED displays  
have a sub-pixel size dictated by the dimensions of a single LED, which can  
be quite small since it is defined by semiconductor lithography  
( $\approx 1\mu\text{m} \times 1\mu\text{m}$  or less). The rapid modulation speed of the LEDs allows a  
20 time modulated grey scale. For example, for  $n$  gray-levels the LED switches  
on 0- $n$  times inside of a single cycle.

LED displays entered the market place as a replacement for vacuum tube  
displays and are still used as small indicators on instruments and small  
25 alphanumeric devices in hand-held computers. However, they have lost  
market share to other technologies in areas where their substrates and  
fabrication costs lead to higher prices, where the power consumption of  
LEDs was not competitive, or where full color was desired. Recently, these  
arguments favoring LCD and other technologies have become less  
30 important for several reasons. First, progress in materials science and  
technology have improved LED power efficiency and color gamut, and  
further progress can be expected. The power advantage of LCDs is  
significant mainly in nonemissive mode where the LCD is illuminated by

- 1 ambient light and acts only as a reflective or transmissive spatial filter. Increasingly LCD applications require a lamp, for example in high-brightness displays for laptop computers.
- 5 LED displays are attractive when maximum viewing angle, fast response speed, and minimal pixel size are desired. However, the prospects of LED displays depend on the solutions of numerous problems, for example the color gamut and the integration of addressable LEDs of different color onto a reasonable sized display panel.
- 10 Whereas 10 inch diagonal AM LCDs are common and systems four times as large are in an experimental stage, the size of monolithic LED displays is limited between 2 and 25 mm by the available crystalline substrates size. Larger LED based displays have been developed, but from discrete devices.
- 15 It becomes obvious from the above description that there is a need for cheaper, lighter, and less complex display assemblies. In addition, there is a demand for displays with improved resolution, in particular for HMD and projection displays, but also for video, computer, TV, wrist watch, and
- 20 handheld computer displays. Another important design criterion is the power consumption because portable systems depend on batteries. Furthermore, displays are preferred that require low voltage light sources for safety, cost weight and simplicity concerns.
- 25 It would be advantageous to replace the light sources for today's light modulating display panels, or the LEDs of light emitting diode displays by a monolithic semiconductor light source emitting bright primary colors. Monolithic multicolor LED arrays providing a 1- or 2-dimensional distribution of individually addressable light sources on a substrate and
- 30 providing two or more distinguishable colors are not known in the art. A special unsolved problem is the integration of LEDs capable of covering the entire visible spectrum. Another problem is to develop a display assembly which optimally employs such a LED lamp.

1 In the following, the color capabilities of visible LEDs with special emphasis  
on the integration of different colors on the same substrate are briefly  
summarized as it is known in the art. Discrete monochrome LEDs across  
the entire visible spectrum are known. An overview is given in textbooks  
5 such as "Flat-Panel Displays and CRTs", edited by L. E. Tannas, Van  
Nostrand Reinhold Company, Chapter 9, pp. 289-331, 1985. In the majority  
of applications, either direct electronic band-to-band transitions or  
impurity-induced indirect transitions in the material forming the active  
region of the LED are used for light generation. With band-band transitions,  
10 the energy gap of the material chosen for the active region of the LED, i. e.  
the zone where the electronic transitions responsible for the generation of  
light within the LED take place, determines the color of a particular LED.  
With impurity induced indirect transitions, the energy spacing between the  
impurity and the band in the active region determines the color. A related  
15 concept for tailoring the energy of the dominant optical transition of a  
particular material and thus the wavelength of the generated light is the  
incorporation of impurities leading to the introduction of deep traps within  
the energy gap. In this case, the dominant optical transition takes place  
between a band-state of the host material and the energy level of the deep  
20 trap. Therefore, the proper choice of an impurity can lead to radiation at  
photon energies of any energy below that of the energy gap of the host  
semiconductor. In this case, the impurity, the host-semiconductor and the  
exact alloy composition chosen for the active layer offer three degrees of  
freedom for the design of a LED with a particular wavelength since the  
25 bandgap induced shift in the impurity levels in alloys also can change the  
emission color.

Today, exploiting these two concepts for tailoring the emission wavelength  
of an LED and using III-V, II-VI, or IV-IV compound semiconductors and their  
30 alloys for the active region of the LED, it is possible to cover the full visible  
spectrum between near infrared and near ultraviolet. However, due to  
constraints on the growth of high quality semiconductor layers, a general  
problem is the feasibility of combining materials, doping conditions and

- 1 device concepts for LEDs such that different wavelengths can be generated from the same base material in monolithic form.

5 In the majority of LED technologies, the active region is placed between appropriate semiconductor cladding layers, one being doped p-type and the other n-type. The optical transitions are induced by injecting electrons and holes into the active layer via an applied bias across the cladding layers. An important and sometimes restrictive premise of this approach is the existence of proper cladding materials which can be doped p- as well as  
10 n-type and can serve as substrates for the fabrication of high quality active region. Examples of common materials for p-n-type LED active regions and the wavelengths for which they are best suited at room temperature are summarized in the following.

- 15 Direct band-to-band transitions in GaAs are used for the generation of infrared light at around 870 nm. Exploiting direct band-to-band transitions in  $\text{Ga}_x\text{Al}_{1-x}\text{As}$ , the infrared/red spectral range between about 867nm and about 652nm can be covered by the appropriate molar fraction  $x$ . The material system  $\text{GaAs}_{1-x}\text{P}_x$  is suitable for the spectral range 867nm - 610nm  
20 (i.e. infrared - red) when exploiting direct transitions ( $x < 0.49$ ), and appropriate for 610nm - 548nm (i.e. red - green) when taking advantage of indirect band-to-band transitions, enabled by isoelectronic impurities induced processes from impurities such as nitrogen and ZnO.

- 25 For blue light generating LEDs, wide bandgap semiconductors such as SiC, GaN, AlGaN, InAlGaN, ZnSe/CdZnSe or CdZnSeS are all used. Until recently, the majority of these wide bandgap materials could not be grown both p- and n-doped. Therefore, LEDs based on conventional p-n-junctions for carrier injection into the active region were not feasible. To circumvent  
30 this inconvenience, MIS-type (metal insulator semiconductor) diodes were successfully applied. In MIS-type LEDs, the active layer is made insulating by deep impurity levels and sandwiched between a conductive semiconductor layer and a metal contact. By applying an appropriate bias

1 between the metal and conductive semiconductor layer, electrons are injected into the active layer, whereby the electron emitter is usually the negatively biased n-type semiconductor layer. Once in the active layer, the injected electrons radiatively recombine with holes at the impurity sites, which are refreshed by the counter electrode or impact ionization. Such structures show typical diode-like nonlinear current-voltage characteristics including a threshold voltage and an exponential increase of the injected current as a function of the applied bias.

10 Blue light emitting MIS diodes have been realized in the GaN system. Examples of these have been published in:

- "Violet luminescence of Mg-doped GaN" by H. P. Maruska et al., Applied Physics Letters, Vol. 22, No. 6, pp. 303-305, 1973,
- 15 - "Blue-Green Numeric Display Using Electroluminescent GaN" by J. I. Pankove, RCA Review, Vol. 34, pp. 336-343, 1973,
- "Electric properties of GaN: Zn MIS-type light emitting diode" by M. R. H. Khan et al., Physica B 185, pp. 480-484, 1993,
- "GaN electroluminescent devices: preparation and studies" by G. Jacob et al., Journal of Luminescence, Vol. 17, pp. 263-282, 1978,
- 20 - EP-0-579 897 A1: "Light-emitting device of gallium nitride compound semiconductor".

In these documents, a common substrate for GaN is used, namely sapphire. On the sapphire substrate, a thick (several 100 $\mu$ m) layer of n-type GaN was grown, often unintentionally doped. On top of the n-GaN layer, the active layer of insulating GaN was grown. The insulating nature was realized by the incorporation of acceptors such as Zn, Cd or Mg during growth which compensate intrinsic donors and thus reduce the conductivity. Metals such as In, Ni, Ag, or Al served as metal contacts to the insulating active layer. As the sapphire substrate is insulating, special attempts are necessary to apply a bias to the MIS-diode. For making a contact to the n-GaN layer, either side contacts at the edges of the substrate are formed, or the n-GaN

1 layer is made accessible from above by etching contact holes through the insulating GaN active layer.

It has also been recognized in the above-mentioned documents that the  
5 compensation of the insulating GaN layer by impurities such as Zn, Cd, or Mg can lead to different coexistent impurity levels within the energy gap of the host semiconductor whereby the density of the impurity states depends on the doping conditions, i. e. on the type of impurity, its concentration and/or the growth conditions. It is further known that the dominant  
10 electronic transitions which contribute to the electroluminescence of the compensated GaN layer take place between the lowest conduction band and an impurity state within the energy gap. Therefore, depending on the energy of the impurity states involved in the electroluminescent processes, light is generated with photon energies of the bandgap reduced by the binding  
15 energy of the impurity state. Therefore, by appropriate tailoring of the distribution of impurity states, the peak of the GaN electroluminescence spectrum, which is in the ultraviolet if band-to-band transitions are dominant, is red-shifted by the introduction of impurities. Based on this concept, GaN MIS-LEDs have recently been fabricated with peak  
20 wavelengths in the blue, green, yellow, orange and red part of the spectrum, altogether spanning the entire visible spectrum. The quantum efficiency as well as the threshold voltage of such devices are related to the color of their radiation. Quantum efficiencies of about 0.5% and 0.1% have been demonstrated for the green-yellow and for the blue part of the visible  
25 spectrum, respectively. Typical threshold voltages are 4V for the blue, 5V for the green, and 10V for the yellow.

Recently, progress in the development of techniques for p-doping of GaN and related compounds such as InGaN and AlGaIn, led to the first  
30 demonstration of a discrete p-n-type blue GaN based LED. One example representing the state of the art is given in "Candela-class high-brightness InGaIn/AlGaIn double-heterostructure blue-light-emitting diodes" by S. Nakamura et al., Applied Physics Letters, Vol. 64, No. 13, pp. 1687-1689,

1 1994. The vertical layer structure of the LED disclosed in this article consists  
of a stack of GaN/AlGaIn/InGaIn layers grown on sapphire. The active layer  
consists of Zn doped InGaIn sandwiched between p- and n-doped AlGaIn  
layers, the sandwich forming a double-heterostructure. The Zn doping leads  
5 to optical transitions whose energy is related to the energy of Zn-related  
impurity states in a similar way as it is known for GaN (see above). Since  
the sapphire substrate of this device is not conductive, contact holes are  
etched through the active layer to gain access to the n-GaN layer  
underneath.

10

In summary, using different semiconductor materials, their alloys and the  
incorporation of impurities, different materials for active layers of LEDs are  
available to fabricate discrete LEDs emitting light at any wavelength  
spanning the entire visible spectrum. However, concepts to integrate  
15 different LED-based light sources with multicolor capability on a single  
substrate and using such multicolor source for display applications are  
barely developed.

Variable hue GaN MIS-LEDs which change their color as a function of bias  
20 are known from the article "GaN electroluminescent devices: preparation  
and studies" by G. Jacob et al., Journal of Luminescence, Vol. 17, pp.  
263-282, 1978. The wavelength tuning of such LEDs is based on the  
coexistence of different impurity levels in the energy gap of the host  
semiconductor and the bias dependence of their occupation with electrons.

25 At low bias, the transitions with the lowest energy occur. However, with  
increasing bias, the emission due to this transition saturates, whereas a  
transition with a higher energy appears with increasing intensity and begins  
to dominate the electroluminescence spectrum at even further increased  
bias. The article cited above gives the example of a GaN MIS-LED which  
30 mixes yellow and blue light with an increasing share of blue light as a  
function of increasing bias, both colors being generated in the same active  
region.

1 A variable hue LED which resembles the preceding example was previously disclosed in the article "Variable Hue GaP Diodes" by W. Rosenzweig et al., Solid-State Electronics, Vol. 14, pp. 655-660, 1970. In this case, GaP is the host material and nitrogen and ZnO are used as dopants to generate  
5 impurity states giving rise to electroluminescence at two wavelengths, red and green. The intensity of each color was a complex function of the bias and impurity concentrations.

Another concept of integrating different LED-based light sources with  
10 different colors on a single substrate is the vertical integration of different active regions, each contributing to one particular emission line. One example in accordance with this approach is given in the article "A Multi-Color GaP LED Flat Panel Display Device" by T. Niina, 1981 DID Int. Symp. Digest Technical Papers 12, pp. 140-141, 1981. The device disclosed  
15 consists of a stack of GaP layers, alternatively doped n-, p-, p-, and n-type, thus forming two p-n-junctions on top of each other which are electrically isolated from each other. The active region in one p-n-junction is doped such that impurity induced indirect band-to-band transitions result in the radiation of green light (see above). The other p-n-junction contains ZnO  
20 impurities enabling the generation of red light with photon energies below the energy gap of GaP due to transitions to impurity levels within the bandgap. In order to bias both p-n-junctions independently, three electrodes are necessary whereby complicated processing steps are required for their fabrication. The possibility of independently biasing each p-n-junction  
25 allows for the generation of any intermediate color between red and green. Single elements of such 2-color LEDs have been made and used as picture elements of large LED flat panel displays for TV applications.

Up to now, these concepts have not been extended to provide a simple,  
30 efficient, low voltage, lightweight and bright light source which is suitable as building block of an LED display or illumination of a display panel.

1 However, the concept of monolithic integration of an array of multicolor  
LEDs, is addressed and claimed in the copending PCT patent application  
with application number PCT/EP 94/03346, which was filed on 10 October  
1994. This application relates to arrays of LEDs which are in principle suited  
5 for use in a display assembly. This patent application is incorporated by  
means of reference into the present description and the priority of PCT/EP  
94/03346 is herewith claimed.

It is an object of the present invention to provide a small, efficient and  
10 robust multicolor or 'white' lamp.

It is an object of this invention to provide a monolithic semiconductor array  
of LEDs for the generation of light at multiple wavelengths suitable for use  
as building block for LED displays or as light source for light modulating  
15 display panels.

It is a further object of this invention to provide a monolithic array of LEDs  
emitting light of the three primary colors.

20 It is a further object of this invention to propose such a monolithic array of  
LEDs which are simple and cheap to manufacture.

It is a further object of this invention to propose appropriate materials for  
the LEDs and the substrates.  
25

It is a further object of this invention to provide display assemblies and  
applications incorporating monolithic multicolor LED array light sources and  
to provide an interface circuitry for optimally driving such display  
assemblies.  
30

It is a further object of this invention to provide display applications  
incorporating the monolithic semiconductor arrays of LEDs for displays with  
special emphasis on head-mounted and projection full color displays with

1 gray-scale and video capability, whereby the term full color denotes the capability of representing any color of the visible spectrum.

### SUMMARY OF THE INVENTION

5 The above-mentioned objects are achieved by the devices and display assemblies hereafter claimed.

### DESCRIPTION OF THE DRAWINGS

10 The invention is described in detail below with reference to the following schematic drawings:

15 **FIG. 1A** shows an example of a layered structure of semiconductors on top of a planar substrate for the fabrication of multicolor vertical MIS-type LED arrays.

20 **FIG. 1B** shows an example of a layered structure of semiconductors on top of a planar substrate for the fabrication of multicolor vertical p-i-n type LED arrays.

25 **FIG. 1C** shows an example of a layered structure of semiconductors on top of a planar substrate for the fabrication of multicolor lateral p-i-n type or MIS-type LED arrays.

**FIG. 2A** shows a schematic cross section of an array element with three vertical MIS-type LEDs on a non-conductive substrate.

30 **FIG. 2B** shows a schematic cross section of several vertical MIS-type LEDs on a conductive substrate.

- 1     **FIG. 2C**     shows the schematic top view of an array, derived from the one shown in Figure 2A, comprising two monolithically integrated vertical LEDs.
- 5     **FIG. 2D**     shows the schematic top view of an array, similar to the one shown in Figure 2B, comprising three monolithically integrated vertical LEDs.
- 10     **FIG. 3**     depicts a portion of a multicolor MIS-LED array with a lateral arrangement of the electron emitter and active regions, which is suited for display assemblies, in accordance with the present invention.
- 15     **FIG. 4A**     shows a schematic cross section of a monolithic array with two vertical p-n type LEDs on a non-conductive substrate.
- FIG. 4B**     shows a schematic cross section of a monolithic array with two vertical p-n type LEDs on a conductive substrate.
- 20     **FIG. 4C**     depicts a portion of a monolithic multicolor p-n type LED array with a lateral arrangement of p-type and n-type regions with the compensated active regions between, which is suited for display assemblies, in accordance with the present invention.
- 25     **FIG. 5A**     is a schematic, perspective view of a light modulating display assembly, in accordance with the present invention.
- FIG. 5B**     is a schematic, perspective view of the display assembly of Figure 5A, at  $t=t_1$ , i.e. while only the red diode of the array emits light.
- 30

- 1     **FIG. 6**     is a timing diagram, which shows an example of the signals for driving one red, green, and blue diode of an LED array lamp, and the signal for activating the pixels of a light modulating display panel.
- 5     **FIG. 7**     shows a conventional display panel with pixels and subpixels.
- FIG. 8**     shows a single light modulating display panel, in accordance with the present invention, at the times  $t=t_1$ ,  $t=t_2$ , and  $t=t_3$ .
- 10    **FIG. 9A**    is the schematic top view of a display assembly comprising a small, point-like light source, a lens, and a light modulating display panel.
- 15    **FIG. 9B**    is the schematic side view of the display assembly of Figure 9A, wherein said light modulating display panel is operated in the transmissive mode.
- FIG. 9C**    is the schematic side view of the display assembly of Figure 9A, wherein said light modulating display panel is operated in the reflective mode.
- 20    **FIG. 10A**   is the schematic top view of a small monolithic multicolor array of LEDs.
- 25    **FIG. 10B**   is the schematic top view of a small monolithic multicolor array of LEDs.
- FIG. 10C**   is the schematic top view of a monolithic multicolor array of LEDs.
- 30

1     **FIG. 11**     is the schematic top view of a display assembly, comprising a multicolor source, in accordance with the present invention.

5     **FIG. 12A**    is the schematic top view of a display assembly, comprising a 1- or 2-dimensional multicolor lamp, a total reflection internal (TIR) mirror element and a transmissive display panel, in accordance with the present invention.

10    **FIG. 12B**    is the schematic top view of a display assembly, comprising a 1- or 2-dimensional multicolor lamp, a total reflection internal (TIR) mirror element and a reflective display panel, in accordance with the present invention.

15    **FIG. 12C**    is the schematic top view of an off-axis display assembly, comprising a 1- or 2-dimensional multicolor lamp, a mirror element and a reflective display panel, in accordance with the present invention.

20    **FIG. 13A**    is the schematic top view of a display assembly, comprising a 1- or 2-dimensional multicolor lamp, a low angle total internal reflection (TIR) mirror element and a reflective display panel, in accordance with the present invention.

25    **FIG. 13B**    is the schematic top view of a display assembly, comprising a 1- or 2-dimensional multicolor lamp, a low angle total internal reflection (TIR) mirror element and a transmissive display panel, in accordance with the present invention.

30    **FIG. 14A**    is a schematic top view of a HDM comprising two display assemblies, in accordance with the present invention.

**FIG. 14B**    is a schematic front view of the HDM illustrated in Figure 13A.

- 1 **FIG. 15** is a schematic top view of another HDM comprising two display assemblies each of which having a multicolor point or line source, a collimator lens and a reflective display panel, in accordance with the present invention.
- 5 **FIG. 16** is a schematic top view of yet another HDM comprising two display assemblies similar to the assembly illustrated in Figure 13A.
- 10 **FIG. 17** is a schematic block diagram of a display assembly and interface circuitry, in accordance with the present invention.
- FIG. 18** is a schematic block diagram of another display assembly and interface circuitry, in accordance with the present invention.

15

#### GENERAL DESCRIPTION

In the above mentioned, copending PCT patent application, monolithic multicolor light emitting diode (LED) arrays are described. Different  
20 approaches are addressed in this application to obtain an array of LEDs which emit light at different wavelengths.

For sake of convenience, the basic concept of the arrays disclosed and claimed in the above PCT patent application is outlined in the following. In  
25 connection with Figures 1A and 1B the basic principle of MIS LEDs and p-n LEDs is described. In Figures 2, 3, and 4 several monolithic multicolor LED arrays are shown, which are described afterwards. Based on these different monolithic multicolor LED arrays, special embodiments of the present invention are developed.

30

In the following, multicolor LED arrays, as described in the above PCT patent application, based on the material system  $(\text{Al}_x\text{Ga}_{1-x})_y\text{In}_{1-y}\text{N}$  ( $0 \leq x, y \leq 1$ ) are shown. The reason for this particular choice of a material

1 system is twofold. First, for some members of this family of materials,  
doping dependent electroluminescence in many colors has been  
demonstrated, as mentioned in the introductory portion. Second, this family  
of materials includes wide-bandgap semiconductors and is, therefore, a  
5 candidate for full color light sources covering the entire optical spectrum  
between near-infrared and near-ultraviolet. Such color light sources are  
well suited for use in displays.

On the other hand, doping-induced multicolor electroluminescence is not  
10 limited to  $(\text{Al}_x\text{Ga}_{1-x})_y\text{In}_{1-y}\text{N}$  and can be considered as a general concept for  
semiconductors. For example, GaP doped with N leads to green  
electroluminescence and GaP doped with ZnO leads to red  
electroluminescence (see introductory part). Thus, the particular choice of  
the material system  $(\text{Al}_x\text{Ga}_{1-x})_y\text{In}_{1-y}\text{N}$  does not mean any loss of generality  
15 concerning the multicolor capability of semiconductor materials. However,  
 $(\text{Al}_x\text{Ga}_{1-x})_y\text{In}_{1-y}\text{N}$  has the advantage of offering multicolor capabilities with  
an extreme spectral width compared with materials having a narrower  
energy gap. Other wide-bandgap semiconductors, such as II-VI and IV-IV  
compounds, serve for the same purpose.

20

There are two different geometrical arrangements disclosed in the  
copending PCT application, the first being characterized by a vertical  
injection of carriers into the active region, whereas the second is based on  
a lateral injection (with respect to the substrate). First, the vertical  
25 arrangement is discussed.

25

Figures 1A and 1B show layered semiconductor structures based on  
 $(\text{Al}_x\text{Ga}_{1-x})_y\text{In}_{1-y}\text{N}$ . These layered structures are considered as starting  
points for the fabrication of embodiments of this invention. They are kept as  
simple as possible, i.e. only one layer serves as active layer for the entire  
30 multicolor LED array. The layered structures shown in Figure 1 are used in  
the following for explanation of the differences between MIS- and p-i-n -type  
diodes.

1 Initially, we discuss only devices based on crystalline materials. However, the basic concepts being summarized in the following can be extended to other states of solid matter, e.g. to polycrystalline or amorphous material.

5 Figure 1A shows an example of a layered structure of semiconductors on top of a planar substrate for the fabrication of multicolor MIS-type LED arrays. Several substrates are suitable for devices based on crystalline  $(\text{Al}_x\text{Ga}_{1-x})_y\text{In}_{1-y}\text{N}$ , for example sapphire, SiC, Si, ZnO or AlGaInN. Sapphire, which is insulating, is the substrate traditionally used. The application of  
10 SiC, Si, ZnO and AlGaInN as suitable substrates is also known, but not as widespread. Below, it is shown that it is the good conductivity of SiC, Si and AlGaInN of which advantage can be taken, because due to this property, means for applying a bias to a particular LED in a LED array can be simplified. Such a simplification is one of the objects of this invention. Both  
15 substrates, sapphire and SiC, are transparent to visible light and permit the LEDs to be designed such that the light generated is preferably emitted through the substrate into the halfspace below the substrate (whereby the term 'below' corresponds to the backside of substrate, i.e. the side not being used for the deposition of the layers of semiconductors). Of course,  
20 LED arrays based on the structures in Figure 1 can be designed such that the electroluminescent light directed towards the halfspace above the substrate is used.

High-quality crystalline layers of  $(\text{Al}_x\text{Ga}_{1-x})_y\text{In}_{1-y}\text{N}$  can be grown by means  
25 of epitaxy methods such as metal organic vapor phase epitaxy (MOVPE) or molecular beam epitaxy (MBE). Typical growth conditions are for example described in:

- EP-0-579 897 A1

30 - EP-0-551 721 A2

- "GaN, AlN, and InN: A review" by S. Strite et al., Journal of Vacuum Science and Technology, Vol. B 10, pp. 1237-1266, 1992.

1 From these references, descriptions of standard device processing steps, such as etching processes, doping  $(\text{Al}_x\text{Ga}_{1-x})_y\text{In}_{1-y}\text{N}$  p- and n-type during and after crystal growth with a variety of dopants (e. g. Zn, Cd, Si, and Mg), and the formation of metal coatings resulting in either Schottky barriers or  
5 ohmic contacts can be taken. Such fabrication steps are considered as known and are hereinafter not discussed in detail.

The layered structure shown in Figure 1A comprises a conductive  $n - (\text{Al}_x\text{Ga}_{1-x})_y\text{In}_{1-y}\text{N}$  layer 11 on top of the substrate 10, and a further  
10  $(\text{Al}_x\text{Ga}_{1-x})_y\text{In}_{1-y}\text{N}$  layer 12 serving as active layer of the LEDs to be realized. The first-grown  $n - (\text{Al}_x\text{Ga}_{1-x})_y\text{In}_{1-y}\text{N}$  layer 11 is either undoped and its n-type conductivity relies on native defects (i.e. unintentionally-doped), or its conductivity is further increased by n-doping, e.g. by adding donors such as Si or Ge during growth. For fabrication of a MIS-type LED based on the  
15 layered structure in Figure 1A, the top layer 12 must be made insulating by compensating impurities. In accordance with this invention, different doping procedures are suitable, depending on the particular application. This doping can be performed either during or after growth of the active layer. For the electrical compensation, the same impurities which lead to the  
20 multicolor capability of the active layer can be used.

To create the multicolor capability of the inventive LED arrays a lateral variation of the doping conditions in the active layer is needed. It is favorable to perform the doping after the growth of the active layer. The  
25 large lateral variation of the doping conditions required in this case cannot be easily controlled during growth of the active layer in the present state of the art. An approach to realize a large lateral variation of the doping conditions is described in the copending PCT application.

30 In Figure 1A, the first semiconductor layer 11 grown on the substrate 10 is characterized as being n-type. However, the MIS-LEDs to be discussed in the following function also with the first semiconductor layer being p-doped. In this case, the sign of the operating bias needs to be reversed.

1 For the thickness of the insulating layer 12 in Figure 1A, trade-offs exist leading to optimized values. The thickness of the active layer is typically in the range of 20nm - 1 $\mu$ m.

5 Figure 1B depicts a second layered structure, suitable for multicolor p-i-n type LED arrays, which serves as a building block for further embodiments of the present invention. The layer sequence 15 - 18 chosen, is in some respects similar to a known structure cited in "Candela-class high-brightness InGa<sub>N</sub>/AlGa<sub>N</sub> double-heterostructure blue-light-emitting diodes" by S. Nakamura et al., Applied Physics Letters, Vol. 64, No. 13, pp. 1687-1689, 1994. We adopt in the following the idea of using a double hetero-structure consisting of an active layer 17 (Al<sub>x</sub>Ga<sub>1-x</sub>)<sub>y</sub>In<sub>1-y</sub>N sandwiched by two (Al<sub>u</sub>Ga<sub>1-u</sub>)<sub>v</sub>In<sub>1-v</sub>N cladding layer 16 and (Al<sub>m</sub>Ga<sub>1-m</sub>)<sub>n</sub>In<sub>1-n</sub>N cladding layer 18, one being p-doped, the other being  
15 n-doped. The mole fractions x, y, u, v, m and n are chosen such that a heterobarrier occurs at the interfaces between active and cladding layers (e.g. with x=0, y=0.5, v=1, u=0.5 m=1, n=0.5). For n- and p-doping of the cladding layers, Si and Mg, respectively, can be used as dopants. In the above-mentioned article, a single blue-light emitting LED is disclosed which  
20 benefits in terms of brightness and wavelength redshift from impurity related transitions in the active layer, whereby the impurity Zn has been introduced during growth, leading to a homogeneous doping of the active layer. However, in the framework of this invention, the doping has a different role, namely to introduce multicolor capability. Doping with a large  
25 lateral variation of the profile performed after growth of the active layer 17, as discussed in the context of Figure 1A, can be applied.

Figure 1C depicts a third layer structure which is suitable for the fabrication of either MIS or p-i-n LEDs using the techniques to be disclosed below, with  
30 the difference that the electrical conduction is lateral, parallel to the substrate plane.

1 In the next step, it is shown how structures like those depicted in Figure 1  
can be doped with a large lateral variation of the doping conditions. This  
doping is not only used in the following for adding multicolor capabilities  
but also for a modification of the conductivity of semiconductor layers in the  
5 lateral direction. This latter application is relevant for the electrical isolation  
of adjacent devices in arrays and the formation of laterally conducting LED  
devices. The task of doping semiconductor layers after growth including the  
control of a lateral variation of the doping conditions is divided into a mask  
step with a subsequent doping step, whereby several steps of this kind may  
10 be sequentially carried through. During a mask step, the surface of the  
semiconductor structure to be modified by doping is covered by a mask  
such that only certain islands on top of the surface are accessible for  
dopants. During the subsequent doping step, the masked semiconductor  
structure is exposed to dopants. For doping, all methods are adequate  
15 which allow for the controlled incorporation of dopants into a defined  
volume of a semiconductor structure through the surface of this structure.  
Examples of such doping methods are ion implantation or vapor deposition  
over a wide range of temperatures. An additional annealing leads to a  
redistribution of dopants by diffusion within the sample and/or to annealing  
20 of defects. The annealing is optional for ion-implantation since in this case,  
its function is mainly to activate dopants rather than to redistribute them.  
However, after vapor deposition, annealing is mandatory for the  
incorporation of dopants into a semiconductor structure. The so-called  
'doping conditions' can be described by a set of parameters which  
25 characterize the doping process as completely as possible. The most  
important ones are the kind of incorporated dopants and their local  
concentration described by a 3-dimensional doping profile. In general, if n  
different doping conditions must be realized at different locations of a  
semiconductor layer, n different mask steps with a subsequent doping step  
30 must be performed.

For GaN-based LEDs, a laterally varied dopant profile can be realized by  
using a mask and conventional lithography to pattern holes or vias into an

1 overlayer, which can be  $\text{SiO}_2$ ,  $\text{SiN}_x$ , or photoresist. Through these openings,  
the dopants can be introduced into the GaN or onto the surface for later  
annealing. This kind of mask fabrication is conventional for GaN-based  
devices. Processing steps related to it can be taken from the  
5 above-mentioned reference EP-0-579 897 -A1.

Examples for doping conditions which can be achieved with the  
above-mentioned doping procedures and allow for a compensation of n-type  
GaN and lead to electroluminescence of GaN in different sections of the  
10 entire visible spectrum are known from the article

- "Photoluminescence of ion-implanted GaN" by J. I. Pankove et al., Journal  
of Applied Physics, Vol. 47, No. 12, pp. 5387-5390, 1976,

15 and the other references mentioned above in the context of GaN-based  
MIS-LEDs. Equivalent data for other members of the family  
 $(\text{Al}_x\text{Ga}_{1-x})_y\text{In}_{1-y}\text{N}$  can be considered as being a continuous function of  
x and y.

20 It is now shown in detail how the above-mentioned mask steps and doping  
procedures are used for the fabrication of monolithically integrated  
multicolor LED arrays. In order to give a few examples, the structures  
shown in Figure 1 are used as starting points. Schematic cross sections  
through three-color LED arrays along one line of LEDs are shown, and the  
25 main fabrication steps of these particular arrays are described. Cross  
sections in other directions would be qualitatively equivalent. Differences  
can appear in the context of electrical isolation between different single  
devices, for example the isolation of LEDs in x-y line-addressable LED  
arrays. Such differences are discussed later when arrays with a higher  
30 density of diodes are treated.

1 The cross-section of an LED array, in accordance with the present invention, is shown in Figure 2A. It is a three-color MIS LED array made from the layered semiconductor structure in Figure 1A. It is assumed that

- 5 • the substrate 30 (being equivalent to layer 10 in Figure 1A) is not conductive, e.g. sapphire;
- the LEDs represent light sources whose shape observed in the direction perpendicular to the substrate 30 corresponds roughly to the size and arrangement of the metal contacts on the active layers 34.x (with  $x = 1, 2, \dots$ ) (being equivalent to layer 12 in Figure 1A);
- 10 • each LED can be biased via one individual metal contact 33.x ( $x = 1, 2, \dots$ ) on top of the active layers 34.x this contact not being shared with other LEDs, and another, common contact 32 which is shared with other LEDs, on the same row or column.
- 15 • the electrical current through the active layers 34.x of the LEDs is mainly perpendicular to the substrate 30 since the active layer is thin and its resistivity is high in comparison to the adjacent layers.
- 20

The following steps are required to arrive at the device structure shown in Figure 2A when starting with the layered semiconductor structure in Figure 1A. Layer 12 is intended to become the active layers 34.x of the LEDs shown in Figure 2A. Therefore, it must be compensated with impurities as described above in accordance with the specified colors of the light sources to be fabricated. Since individual diodes with three different colors are desired, at least three different mask steps with subsequent doping steps are required, each step defining the doping conditions for the active areas of the entire set of equivalent LEDs in the array. The hatched areas in all Figures of the present application indicate regions which have been doped in one of the before-mentioned doping steps. These areas are marked with the symbols  $D_i$  ( $i = 1, 2, \text{ and } 3$ ) in order to distinguish between

25

30

1 regions with different doping conditions. The shape of a particular island  $D_i$ ,  
being characterized by constant doping conditions has not to be identical  
with the shape of light sources fabricated. Since the shape of the metal  
contact defines the light pattern emitted by the LEDs, transparent metals  
5 (e. g. ITO, i. e. indium tin oxide) or semitransparent thin metal layers or  
combinations thereof can be used for the metal contacts if it is desired to  
collect the light out of the metal-contact side. If non-transparent metals are  
used for the metal contacts, the light of the LEDs could still be collected on  
the contact side. In all of these configurations, the light can easily be  
10 collected through a transparent substrate, probably with better efficiency  
and greater ease.

After the definition of islands with constant doping conditions, contacts for  
applying a bias to each particular LED are realized. The conductive  
15 semiconductor layer 31 of the LEDs serves as a common electrode to all  
LEDs unless device isolation is desired in which case appropriate means for  
electrical isolation such as etching of isolation trenches or deep  
compensating implantations are applied. However, in this particular  
example, it is assumed that each LED is individually addressable by means  
20 of one individual contact on top of the compensated regions  $D_i$  and the  
common bottom contact. Consequently, the conductive layer 31 can be  
used as common electrode for an entire row or column. As the substrate is  
assumed to be non-conductive, a physical contact to the conductive layer 31  
must be realized. This can be done by etching a contact hole through the  
25 top layers 34.x or using side contacts. However, if the LED array is large,  
the conductivity of the doped layer might not be sufficient for side contacts  
to the conductive layer 31. Then, a multitude of contact holes or trenches  
can be etched through the active layers and an appropriate wiring of  
conductive material 32 can be patterned to provide a low series resistance  
30 for all LEDs. For biasing a particular LED, metal contact areas 33.x of  
appropriate shape are defined for each LED on top of the active layers 34.x  
(or  $D_i$ ). Known procedures for the metallurgy (see references cited above)  
and the pattern definition, such as photolithographical steps or printing can

1 be used. The application of these processing steps leads to the structure depicted in Figure 2A.

For addressing each LED independently, different functional elements might  
5 be added. The contacts 32 and 33.x could be connected to independent address lines on top of the structure shown in Figure 2A, thus providing an external electrical connection to each individual LED. This can be helpful for connecting the array to driver electronics. However, other methods known from microelectronic packaging can also be applied, e. g. the contact  
10 areas on the LEDs could be brought into electrical contact with the wiring on a second module through which the external bias to the contact areas can be applied. Since one contact is shared between different diodes, the complexity of the electric wiring is less than it is in cases where each diode requires two individual address lines. This is especially important for lamps  
15 which have lower pixel densities and might be amenable to individual addressing rather than x-y matrix addressing.

The multicolor array shown in Figure 2A can be simplified if the substrate  
30 is conductive (e. g. SiC, Si, InGaAlN). In this case, the doped semiconductor layer 31 in combination with the substrate 30 would serve as a single common electrode and special contact holes for accessing the doped semiconductor layer can be avoided. This simplification is shown in Figure 2B. The simplified structure is equivalent to the structure in Figure 2A. Layer 36 corresponds to layer 31. Only the top contact 32 to the  
25 conductive semiconductor layer is replaced by a contact to the substrate 35, which is in this particular example realized as bottom contact 37, thus leading to a simplification of the fabrication. Top contacts 38.x (with  $x=1, 2, \dots$ ) to the compensated regions  $D_i$  define individual MIS-LEDs. Note the elimination of 32 due to the conductive substrate 35 allows a greater portion  
30 of the surface area to be dedicated to areas which emit light, allowing increased diode density and higher brightness. By making the contacts 38.x smaller than the active regions  $D_i$ , isolation between devices is achieved.

1 Figure 2C shows a schematic top view of a multicolor array 8 comprising  
two monolithically integrated LEDs 34.1 and 34.2. This array 8 is based in  
the structure shown in Figure 2A, with the difference that it comprises just  
two diodes instead of the three diodes shown in Figure 2A. The first diode,  
5 the active layer of which is depicted as 34.1, emits blue light, whereas the  
second diode with active layer 34.2 emits green light. The light generated  
by the diodes of array 8 is either emitted perpendicular to the plane shown  
into the halfspace above the array 8, or through the substrate (which is not  
visible in Figure 2C) into the halfspace below the array. The layers of the  
10 two diodes were grown at the same time. The monolithically integrated  
array 8 serves as basic building block for displays in accordance with the  
present invention, as will be described later. This particular arrangement of  
diodes is characterized in that each diode has a first contact metallization  
33.1 and 33.2, not shared with adjacent diodes, and a common second  
15 contact metallization 32. For some display applications such a two-color  
light source might be used as backlamp. It is to be noted that a three-color  
array, as illustrated in Figure 2D, is required to realize full color displays in  
accordance with the present invention. In the present description we will  
mainly concentrate on such full color displays.

20

Figure 2D shows a schematic top view of another monolithic multicolor  
diode array 9 based on the structure illustrated in Figure 2B. This array 9  
comprises three diodes emitting light at different wavelengths, preferably  
wavelengths corresponding to the three primary colors red, green, and blue.  
25 Only the uppermost layers, i.e. the active layers 39.1, 39.2, and 39.3, and  
the contact metallization 38.1, 38.2, and 38.3 of the diodes are visible in the  
schematic Figure 2D. As before, light can be extracted in the half space  
either above or below the substrate.

30 For sake of simplicity, we will refer to the three primary colors red, green,  
and blue in the following. Any combination of wavelengths might be  
suitable, depending on the application. The particular arrangement of  
diodes shown in Figure 2D is characterized in that each diode has a first

1 contact metallization 38.1, 38.2, and 38.3, not shared with adjacent diodes,  
and a common second contact metallization 37 (see cross section in Figure  
2B). The purpose of this particular arrangement of electrodes is described  
later. The shape of the diodes needs not necessarily to be rectangular.  
5 Based on building blocks like Figures 2C and 2D, larger diode arrays can  
be made. The contact address line metallization might be placed at the  
periphery close to the edge of the diodes. The back contact might likewise  
be realized over only a small fraction of the substrate back so a maximum  
amount of emitted light can escape.

10

It is obvious that this example can be modified in many ways. The colors,  
the number of different colors, the size, the shape and the arrangements of  
the diodes, and the arrangement of the metallization are arbitrary. This  
example illustrates relevant features of this invention, and the particular  
15 arrangements of diodes given in Figures 2B and 2D are suited for multicolor  
displays.

Figure 3 shows a schematic view of a multicolor 2-dimensional x-y  
addressable LED array which is based on lateral MIS-type LEDs. The  
20 fabrication of this particular structure starts from a single layer 21  
equivalent to Figure 1C, which is either undoped (i. e. unintentionally  
doped) or doped during or after growth. This step is followed by the  
introduction of insulating regions by means of the above-mentioned doping  
techniques, whereby the doping conditions are chosen such that the  
25 insulating regions, which serve as active regions of the LEDs, are capable of  
generating radiation with predefined colors. Regions with different doping  
conditions are denoted in Figure 3 with different symbols  $D_i$  ( $i=1, 2, 3$ ).  
Contacts 22, 23, 24, 25 and 29 for applying a bias between an insulating  
region and the conducting region complete a particular LED, whereby - in  
30 contrast to the previous embodiments - the electrons are injected primarily  
laterally into the active regions where they radiatively recombine with  
impurity-related holes.

1 Another embodiment of the array in Figure 3 can include implantations 23.x  
( $x = 1, 2, 3, \dots$ ) to augment the carrier concentration in the conducting  
regions of the device structure. This may be desirable if said impurities are  
only desired in the conducting regions of the devices, and not in the active  
5 regions where they might compensate the deep impurity recombination  
centers causing a reduction in device efficiency. In this case, the single  
layer 21 is grown under conditions which optimally suppress any impurity or  
native defect incorporation, and conductive impurities 23.1 are introduced to  
fill in the space between the active regions  $D_i$  ( $i=1,2,3$ ), using the same  
10 techniques previously disclosed for active region dopant introduction.

Within each row of the array given in Figure 3, all LEDs might share either a  
common ohmic contact 23, in which case the conductive regions can be  
either the entire intermediate regions 23.x ( $x = 1, 2, 3, \dots$ ) between said  
15 active regions D1, D2, D3, or they might share the parts of the intermediate  
regions adjacent to these active regions electrically isolated from the  
neighboring active region.

Under appropriate bias conditions between the ohmic 23 and Schottky 24,  
20 25 and 29 contacts, said conductive layers transport electrical charge  
injected from said ohmic contacts 23 primarily along the substrate plane  
into the said active regions on either side of each ohmic contact leading to  
multicolor electroluminescence whose wavelengths are dictated by the  
impurities in the active regions. Likewise, the LEDs in a single row might  
25 share a common Schottky contact in which case the conductive regions  
adjacent on either side of first active region D1 must be electrically  
isolated from those adjacent on either side of the second active region D2  
from one another by means of electrical isolation 26 between. Under  
appropriate bias conditions between the ohmic and Schottky contacts, the  
30 conductive layers adjacent to each active region on either side transport  
electrical charge injected from their respective ohmic contacts primarily  
along the substrate plane into the said active regions leading to multicolor

1 electroluminescence whose wavelengths are dictated by the impurities in the active regions.

For a suppression of leakage currents between different LEDs and thus  
5 cross-talk between different LEDs, electrical isolation 26 between adjacent LEDs can be introduced. Known isolation approaches are sufficient for the present LED arrays, e. g. etching of deep isolation trenches or doping for introducing current blocking regions such as p-n-junctions or compensated (i. e. insulating) regions. The latter approach is obviously an application of  
10 the above-mentioned doping techniques. As a major part of the electrical current flows close to the upper surface of the semiconductor layer 21, the depth of said isolating regions is an important optimization parameter for minimizing leakage currents. Perfect isolation can be achieved by using an insulating substrate 20 and perfectly suppressing the lateral current between  
15 different LEDs by making the depth of said isolating regions equal to the thickness of the semiconductor layer 21. Means for isolation 27, 28, e. g. thin dielectric layers, assure that the address lines 22-25 and 29 are connected only to appropriate terminals of the LEDs and that individual LEDs can be addressed and activated for the generation of light. A major  
20 advantage of the lateral embodiment is its planarity which considerably simplifies fabrication.

The structure shown in Figure 3 can be modified in different ways within the same concept of lateral injection of carriers into the insulating region of  
25 MIS-LEDs. The basic idea behind these lateral realizations is that they are planar and can be made from a single semiconductor layer grown on a substrate. This semiconductor layer, being the starting point for the fabrication of an array of MIS-LEDs, is intended to be doped either n- or p-type in regions, and insulating in other regions. The MIS-LEDs are  
30 realized by applying the above-mentioned doping techniques to certain regions on the surface of said semiconductor layer and by providing metal contacts. In addition, as in the previous example, isolation of adjacent LEDs are optional. The structure shown in Figure 3, is the simplest one herein

1 described and is thus well suited for low cost display applications, or even discrete monochrome LED applications.

5 Figures 4A and 4B demonstrate the application of the inventive idea to p-i-n LEDs. As an example, it is assumed that the same pattern of diodes, which was discussed in the context of the previous embodiments, is transferred to the layered semiconductor structure depicted in Figure 1B. The major differences in comparison with the MIS-type devices are:

- 10 • The active layer is provided with multicolor capabilities by doping after growth of the layers. An appropriate doping procedure is ion implantation since the distribution of implanted ions can be a peaked function whose characteristics, namely its width and the position of its center with respect to the surface bombarded with ions depend on the  
15 ion energy and on further parameters determined by the nature of the ions and the implanted material, and on the conditions of further optional processing steps such as annealing.
- The top layers 44.x of the structure shown in Figure 4B is conductive.  
20 Therefore, the LEDs must be electrically isolated from each other. This can be done exploiting standard approaches, e. g. by etching isolation trenches through the uppermost cladding layers 44.x and the active layers 43.x or by making appropriate portions of the uppermost cladding layers 44.x insulating, for example by compensation.
- 25 • For p-i-n type LEDs, the shape of the top contact is less important for the shape of the light spot related to a particular LED since a current spreading occurs in the cladding layers due to their conductivity. The shape of the multicolor light sources can be defined either defined by  
30 tailoring the lateral current profile within a particular LED (e. g. by electrical isolation, see above) or by shaping the lateral profile of those dopants which are responsible for the radiative transitions in the active layer.

1 Taking the remarks related to p-i-n type LEDs into account, the  
above-mentioned steps are applied to the layered structure shown in  
Figure 1B, and two multicolor p-i-n type LED arrays are realized. These  
examples are shown in Figures 4A and 4B. Both examples are equivalent  
5 analogs of the MIS-type LEDs in Figures 2A and 2B. In the case of  
Figure 4A, the substrate 41 is insulating. In the case of Figure 4B, the  
substrate 47 is conductive. Again, like in the previous examples, areas with  
constant doping conditions are hatched and the symbols  $D_i$  ( $i=1, 2, \dots$ ) are  
used to distinguish between different doping conditions and thus different  
10 colors of the related light sources. As electrical isolation between adjacent  
LEDs, the option of etching away parts of the uppermost cladding layer and  
the active layer has been chosen. As to approaches to form contacts for  
biasing individual LEDs, the same arguments hold as those given above in  
the context of MIS-devices. In particular, if each LED can be biased via an  
15 individual contact on top the uppermost cladding layer, the lower cladding  
layer 42 can be used as common electrode for all LEDs. Furthermore, if the  
substrate is conductive, it is sufficient even for a large substrate to use one  
common contact 48 to the substrate and one individual top contact 45.x  
(with  $x=1, 2$ ) for each LED for biasing, whereas in the case of an insulating  
20 substrate, one contact 46, or a series of such contacts, to the lower cladding  
layer might be required for large substrates in order to minimize the series  
resistance for all LEDs. A disadvantage of Figures 4A and 4B is that they  
are non-planar, making addressing difficult. they could be useful, however,  
for lamps which need only a small amount of addressing capability.

25

A lateral, monolithic p-i-n LED array is illustrated in Figure 4C. This array  
comprises two rows of p-i-n LEDs. Each LED comprises an active region  $D_i$ ,  
which is compensated by impurities. This active region is surrounded on  
one side by an n-type conductive region 62x and on the other side by a  
30 p-type conductive region 63x. These active regions and the surrounding  
conductive regions are all formed by means of laterally varied impurity  
introduction into a semiconducting layer 61 which is situated on a substrate  
60.

1 Within each row, all LEDs might share a common ohmic contact of one polarity, either n-type (as illustrated in Figure 4C) or p-type, with the ohmic contacts of the opposite type being individually addressable 65, 68, 69. Under appropriate bias conditions between the ohmic contacts 64 and 65,  
5 68, 69 of opposite polarities, said conductive layers transport electrical charge injected from said ohmic contacts 64, 65, 68, 69 primarily along the substrate plane into opposite sides of the said active regions D, leading to multicolor electroluminescence whose wavelengths are dictated by the impurities in the active regions.

10

As illustrated in Figure 4C, neighboring diodes might be isolated from each other by means of isolation trenches 67, or compensating impurity introduction. Diodes of adjacent rows might also be electrically separated from each other by isolation trenches 70, or compensating impurity  
15 introduction.

The LED arrays described above and hereinafter claimed are well suited for use in connection with different kind of display assemblies. The arrays illustrated in Figures 3 and 4, for example, could be used as basic building  
20 blocks for multicolor LED displays, provided that an appropriate electrical wiring and driving circuitry is employed.

Next, the basic principle of a light modulating display assembly will be described in connection with an embodiment shown in Figures 5A and 5B.  
25 A three-dimensional schematic view of a display assembly, in accordance with the present invention, is illustrated in Figure 5A. The monolithic multicolor LED array 9, similar to the one in Figure 2D, is arranged with respect to a light modulating display panel 50 such that the whole backside of this panel 50 is illuminated evenly by each LED in the said array. The  
30 display panel 50 comprises a plurality of pixels 51, each of which can be individually activated. For the sake of simplicity, all pixels being in a non-transmissive state are shown as white pixels, whereas the pixels to which a voltage ( $V_{\text{pixel}}$ ) is applied and which are in a transmissive state, i.e.

1 which are activated, are striped (see Figure 5B). In Figure 5A, a voltage ( $V_{red}$ ) is applied to the first LED 39.3 causing red light to evenly illuminate all of the pixels 51 in the display panel 50. For larger display assemblies it is advantageous to employ monolithic multicolor LED arrays of different dimensions with a plurality of red, green, and blue LEDs for optimal illumination uniformity.

Each LED of the array is driven in a way indicated in Figure 6 which enables FSC operation of the display. According to the present invention, a voltage pulse  $V_{red}$  is applied to the red diode for a short period of time ( $T/3$ ), then a voltage pulse  $V_{green}$  is applied to the green diode, a voltage pulse  $V_{blue}$  is applied to the blue diode, and so forth. The shape of these pulses does not need to be rectangular and the width of the red, green, and blue pulses might be different. This, along with the areal size of each LED, gives an additional degree of freedom in case that for example the green diode emits light less efficiently than the two others. In such a case, one could for example drive the green diode longer to give the impression that all three diodes have the same brightness, or one could make the green LED relatively larger in area to achieve the same effect. Furthermore, the pulses could overlap, to obtain a smoother transition from one color to the next. At the bottom of Figure 6, the drive voltage  $V_{pixel}$  of some pixels 51 of the display panel 50 is shown. In the present example, the pixels driven by the voltage are switched from the non-transmissive state to the transmissive state while the red and green diodes emit light. It is now crucial that the pulse widths, i.e. the frequency, of the signals activating the diodes is chosen such that the change of color is barely perceivable for the viewer's eyes. In case of the example illustrated in Figure 6, the viewer would see a virtual mixture of the colors red and green, giving the impression of yellow.

30 In connection with Figure 5B, it is explained how an image, be it a virtual or real, is generated. An image is generated by modulation of the backlight by the transmissive display panel 50. The pixels serve as a kind of light valve and only the pixels in a transmissive state contribute to the generation of an

1     Image. In the present example, a situation is shown, where the first diode emits red light. This moment is identified in Figure 6 with  $t_1$ . Five pixels forming a cross are activated and a picture of this cross 52 becomes visible for a viewer situated in front of the display panel 50.

5

      The front view of the display panel 50, at the times  $t = t_1$ ,  $t = t_2$ , and  $t = t_3$  is shown in Figure 8. At  $t = t_1$ , the red diode emits red light and the pixels forming the cross are in a transmissive state. At  $t = t_2$ , green light is emitted by the green diode and the same pixels remain in the transmissive state.  
10     While the blue light is emitted by the blue diode, all pixels are switched into a non-transmissive state such that no light penetrates through the panel 50. A sufficiently intelligent driver might even spare energy by also not activating the blue LED in this case, or in the general case, the blue LEDs in the array which illuminate only inactive pixels. This status is shown at  $t = t_3$ .  
15     Only a short sequence is shown in Figure 8, and typically similar sequences would follow so long as the display remained active. A viewer would not be able to see the red and green as distinct colors because the diodes are driven with a pulsed voltage, as shown in Figure 6, such that one color after the other appears in a fast, alternating and regular manner. A sequence of  
20     colors should be repeated at least 10 times per second. With other words, each of the diodes of the monolithic diode array according to the present invention should be switched on and off at least 10 times per second. He would get the impression that a yellow cross is displayed. Due to the alternating illumination of the display panel, each pixel may appear in any of  
25     the three primary colors or in any mixture thereof depending on how long and when this pixel is activated. A conventional LCD color display panel 70 is illustrated in Figure 7 for comparison. As already explained, such a full color display panel has three subpixels 71 - 73, typically a green, red and blue subpixel, which form one pixel 74. One pixel capable of displaying a  
30     mixture of all three colors requires at least three times as much real estate on the display as a pixel scheme without subpixels. In addition, more electric wiring is needed to drive the subpixel of each pixel. Such a conventional LCD color display panel is operated differently. As

1    hereinabove explained, a white light source is employed for illumination of  
the panel 70. Color filters (not shown in Figure 7) filter the red, green, and  
blue light components out of this white light such that the green subpixels  
are illuminated with green light only, the red subpixels with red light, and so  
5    on. The picture of a yellow cross is generated by having all red subpixels  
75 and green subpixels 76 within this cross in a transmissive state, as  
shown in Figure 7. To achieve the same resolution as in Figure 8, one needs  
smaller features. The compensating advantages of SSC are that the  
subpixels need only be 1/3 as fast as in FSC, and that at any given time all  
10    colors are displayed eliminating color flicker.

In Figure 9A, a schematic top view of another embodiment of the present  
invention is shown. The display assembly illustrated in this Figure  
comprises a multicolor light source 91, in accordance with the present  
15    invention. This light source 91 is a monolithic semiconductor array  
comprising at least two LEDs emitting light at two different wavelengths.  
This semiconductor array 91 is arranged with optics 92 such that a display  
panel 90.x ( $x = 1, 2$ ) is evenly illuminated. If the light source 91 is very  
small, effectively a point-source (hereinafter also referred to as  
20    0-dimensional light source or a point like source) it is advantageous to  
employ collimating optics 92 to achieve a homogenous illumination of the  
whole display panel 90.x ( $x = 1, 2$ ). Based on the arrangement in Figure  
9A, two different schematic side views are shown in Figure 9B and 9C, in  
order to illustrated a display assembly based on a transmissive display  
25    panel 90.1, and another display assembly having a reflective display panel  
90.2. Such a transmissive display panel 90.1 is illuminated from the  
backside, as shown in Figure 9B, and the observer is situated in front of the  
display panel 90.1. In case of an assembly with reflective panel 90.2, as  
illustrated in Figure 9C, the observer and the light source are placed on the  
30    same side of the panel.

Schematic top views of different monolithic multicolor arrays, which are  
suitable as lamps for display assemblies in accordance with the present

1 invention, are depicted in Figures 10A through 10C. For sake of simplicity,  
the diodes of these arrays are shown as simple boxes. Neither the contact  
metallization, nor trenches, isolation layers, or the like, are shown. In  
Figures 10A and 10B two monolithic arrays comprising three diodes 95,  
5 96, and 97 are shown. There are numerous different ways to arrange these  
diodes each having advantages for specific applications. An array 98 of  
nine diodes is illustrated in Figure 10C. It has three blue, three green, and  
three red diodes which are dispersed in a regular pattern. Such a diffused  
lamp provides more uniform illumination over a two dimensional plane as is  
10 common for display panels, and may therefore be preferred.

The arrays shown in Figures 5A, 5B, 10A - 10C might be used as light  
source for assemblies similar to the one shown in Figure 9A. They have to  
be arranged such that the whole light modulating display panel is  
15 illuminated uniformly by all colors. To improve efficiency and to guarantee  
red, green, and blue illumination of similar brightness, a single lens, or an  
array of lenses can be employed. Such an array of lenses can be realized  
by means of embossed foils, for example. A lens could be assigned to each  
of the LEDs and the light emitted could be focussed such that a point source  
20 is obtained. A point-source-like or line-source-like diode array can be easily  
mounted in the display assembly and a conventional collimator lens 92  
(see Figure 9A) can be employed for the collimation of the light emitted by  
the source. An advantage of the present invention is that point-like or  
line-like sources of very small size and good brightness can be fabricated.  
25 Small lamps produce radiation which is easy and cheap to collimate.

Based on the different arrays described hereinabove, monolithic multicolor  
light sources for the illumination of light modulating display panels can be  
made. The diodes of these arrays can be arranged in 0-dimensional (i.e.  
30 point-source-like), 1-dimensional, or 2-dimensional form. Using optical  
elements such as mirrors, lenses, prisms, gratings, total internal reflectors,  
fibers and so forth, the light radiated by the lamp can be projected uniformly  
over the display panel. Additional optical elements such as screens, e.g. a

1     concave projection screen, mirrors, lenses, arrays of lenses, total internal reflectors, fibers and prisms might be situated between the light modulating display panel and the viewer's eyes.

5     The top view of another embodiment of the present invention is shown in Figure 11. It is to be noted that this display assembly is intentionally not drawn to scale. A 0- or 1- dimensional array of monolithically integrated LEDs 132, in accordance with the present invention, is arranged with respect to an optical element 133 such that the entire display panel 130 is uniformly  
10     illuminated at near normal incidence. This embodiment is well suited for HMD and other applications where space is restricted, as well as projection applications where low dimensional light sources are desirable (see above). If the lamp 132 is a 0-dimensional LED array, the optical element 133 could be a curved mirror combined with one or more lenses in such a way to  
15     provide uniform illumination of the display 130.

If a 1-dimensional LED array 134 is employed as lamp, a total internal reflective (TIR) device 136, such as the example shown in Figure 12A, could be used to collimate the incident light and uniformly distribute it over the  
20     display panel 135.1. TIR devices 136, as they are known in the art, are commonly two triangular slabs 136.1 and 136.2 of high refractive index materials separated by a thin spacing 137 of a lower refractive index material. The presence of the lower refractive index material causes all of the light incident at an angle below the critical angle for TIR to be reflected  
25     onto the light modulating display panel 135.1. For transmissive mode displays, see 135.1 of Figure 12A, the TIR device 136 can be an isosceles right triangle with materials chosen so that  $45^\circ$  is below the critical angle. The result is perpendicularly incident, uniform and collimated illumination of the display. In reflection mode, the TIR can either illuminate the display at  
30     near normal incidence, in which case it must be optimized to transmit the light reflected from the display with maximum efficiency, or at off normal incidence (see Figure 12B) in which the design of the  $45^\circ$  TIR 136 can be maintained. One disadvantage of the  $45^\circ$  TIR 136 is that it must have a

1 thickness equal to the display dimension which can add undesirable bulk to  
the display assembly. For this reason, lower critical angle TIR devices are  
desired, but require more complex optics. In Figure 12C an off-axis  
arrangement of a monolithic multicolor lamp 138, a triangular slab 139.1 and  
5 a reflective display panel 135.2 is shown. The multicolor lamp 138 might  
either be a 1- or 2-dimensional source, in accordance with the present  
invention.

Two embodiments of display assemblies comprising lower critical angle TIR  
10 devices 139.2 are illustrated in Figures 13A and 13B. The assembly of  
Figure 13A comprises in addition to the slab 139.2 a multicolor 1- or  
2-dimensional source 138 and a reflective display panel 135.2 which reflects  
the incident light towards a viewer. Instead of a reflective display panel, a  
transmissive panel 135.1 is employed in Figure 13B. It is to be noted that  
15 the second slab is not needed in those embodiments where the light passes  
back through the TIR. It is not the object of this invention to disclose the  
optimal details of a TIR assembly. It is the object of this invention to  
disclose that single dimensional arrays of monolithic multicolor LEDs enable  
elegant TIR display assemblies to be realized.

20

A further embodiment of the present invention is shown in Figures 14A and  
14B. A display assembly, in accordance with the present invention, might be  
employed in bifocal glasses or goggles, as shown in this Figure. The  
principle of such a HMD becomes obvious from the top view in Figure 14A.  
25 There is a display assembly for each eye. Such a display assembly  
comprises a 2-dimensional monolithic multicolor array of LEDs 141, which is  
situated at a close distance right behind a transmissive display panel 142.1  
having a matrix of pixels. In order to change the size, focal point, quality,  
and astigmatism of the image displayed, an intermediate lens 143 might be  
30 employed. The properties of these lenses can be individually adapted, e.g.  
by replacement after consultation of an optician. The frame 140 of the HMD  
can take any convenient form and might incorporate one or more battery  
slots 145, and an I/O plug 144 for interface with wireless or wired

1 connection to a signal source. A TV signal or RGB signal, for example,  
could be fed via a cable 147 or wireless IR or RF frequencies to the two  
display assemblies. A front view of this binocular HMD is illustrated in  
Figure 14B. The uppermost part of each eyepiece is the display 141, and the  
5 lower part is transparent and may correspond to a normal corrective lens.  
The properties of the transparent lenses 146 and the lenses 143 of the  
display assembly can be optimized such that the human eye does not need  
to focus at different distances each time when it jumps from information  
displayed on the panel 142.1 to information visible through the lens 146.  
10 This helps to reduce fatigue of the eyes. Another desirable feature which  
could be incorporated would be the ability to flip up or remove the display  
when viewing is not desired., to restore the full field of view of the  
eyeglasses, and to protect the display from wear. The lamp and optical  
components in this case could either also be removable or remain attached  
15 to the glasses.

In Figure 15, the top view of another HMD is shown. This HMD comprises a  
multicolor 0-dimensional or 1-dimensional light source 148, a lens 149, and  
a reflective display panel 142.2 for each eye. The multicolor source 148 and  
20 lens 149 are arranged such that the light is reflected by those pixels of the  
panel 142.2 which are in a reflective mode. The reflected light contributes to  
a picture which is visible to the HMD wearer. The light sources, lenses,  
display panels, batteries and I/O means need to be fixed to the frame in a  
manner that the HMD is lightweight and good looking. The smaller the light  
25 source is, the smaller the optics can be, and the better all the elements be  
integrated into the frame.

Another HMD, with a 1- or 2-dimensional monolithic multicolor array of light  
emitting diodes, is shown in Figure 16. This HMD comprises two optical  
30 systems each of which comprises a lamp 122, a TIR device 123, and a  
reflective display panel 130. The frame 140 of this HMD comprises I/O  
means 144.1 for receiving an IR signal. The arrangement of the array,  
mirror, and display panel are very much the same as in Figure 13A.

1 LED displays making use of multicolor light emitting diode arrays in accordance with the present invention are well suited for use in retinal displays.

5 As becomes apparent from the above description of different embodiments, many arrangements of monolithically integrated LEDs, which emit at least two different colors are suitable for use in display assemblies in accordance with the present invention. In the case of very small, point-source like diode arrays (see for example Figures 10A - 10C) special optical elements such as  
10 lenses, mirrors, and prisms might be employed. There are several approaches known in the art where the whole optical system of the display assembly is folded such that it fits in the frame of a head mounted display, or into a video camera, portable computer, wrist watch, and so forth. The cost for the multicolor arrays herein claimed might become a crucial factor.  
15 The less LED area such an array requires, the cheaper it is. Smaller arrays also decrease the total system cost by reducing the size and cost of optical components, and even the minimum usable display area. Restating the final point, smaller lamps enable smaller displays reducing costs which are normally a function of the display area.

20

A more complex array of LEDs can be desirable in that a multitude of smaller LEDs covering the same area, emitting light of several different wavelengths, are grown on one common substrate. Such an array with higher LED density is more fault tolerant because a few defective LEDs have  
25 little impact on the overall light of the large total number.

It might be advantageous for certain applications to employ an array comprising two monolithically integrated LEDs, e.g. GaN based diodes emitting blue and green light, and a third discrete LED made of another  
30 material, e.g. an AlGaAs diode emitting red light. The smallest sized point sources are amenable to conventional low cost LED packages featuring built in lenses, while being easily capable of providing the necessary 500 Cd/m<sup>2</sup> or less of HMD display screen brightness.

1 The size of the monolithic multicolor LED arrays herein described is typically in the range from 100  $\mu\text{m}$  x 100  $\mu\text{m}$  up to several square millimeters or even square centimeters.

5 The monolithic LED array could be patterned so that minimum light falls on the address metallization or other dead areas of the display panel. This is a viable improvement especially in display assemblies with LCD panel which have a very low aperture ratio. It could also be addressed so that only the LEDs which are required for a specific section of the image are activated, as  
10 opposed, for example, activating all the blue LEDs when only the top left of the image requires blue.

There are special means needed for driving the diodes of the monolithic diode array and the pixels of the display panel. In the following, two  
15 different driving approaches will be addressed. In Figure 17 a first approach, in accordance with the present invention, is shown. The simplified display assembly shown in this Figure comprises a light modulating display panel 150, with pixels 151. This can be considered one sub-unit of an entire display, or equivalently the entire display. An address has been assigned  
20 to each pixel, depending on the position on the display panel. The address (1,1) was assigned to the first pixel in the first row. The second pixel in the same row got the address (1,2) and so forth. The scheme for addressing the pixels was introduced for sake of simplicity and it is to be noted that any other scheme could be used instead. Opposite to the display panel 150,  
25 there is a monolithic array of LEDs 158. This array might have three blue diodes 155, three green diodes 156, and three red diodes 157, or any other arbitrary number, area and arrangement such as suits the application. As shown in Figure 17, the blue diodes, red diodes, and green diodes are each arranged in parallel, such that all of the blue, or the red, or the green  
30 diodes emit light when an appropriate voltage is applied. The interface means 159 for driving the present display assembly, comprises a decoder 152, which receives for example a red-green-blue (RGB) video signal via input channel 153. This decoder 152 either generates a clock signal on its

1 own, or extracts a clock signal from the video input signal. According to the present embodiment, this clock signal is fed to a counter 154, which has at least three different output states. Each time the counter 154 receives a clock pulse the counter switches to the next state.

5 In the following, the operation of the circuitry in Figure 17 will be described by means of a simple example. Let us assume that a small, yellow square having the size of four pixels is to be displayed by the display assembly; in the present example the pixels (1,1), (1,2), (2,1), and (2,2) will be used. To  
10 achieve the impression that these pixels emit yellow light, the pixels need to be activated while the red and green light is emitted. While blue light is emitted (if at all), these pixels remain non-transmissive, or non-reflective, depending on the kind of display panel used. The interface means 159 receives the respective video information, e.g. as RGB video signal, and  
15 performs the following steps:

1. activating of the pixels (1,1), (1,2), (2,1), and (2,2), either together or in a sequence, while the red and green light is emitted,
- 20 2. driving of the red, green, and blue diodes in an alternating, regular and rapid manner,
3. synchronization of the signals for driving the diodes and the signals for activation of the pixels.

25 There are several ways conceivable for the realization of the interface means 159. It is to be noted that the block diagram of Figure 17 is only an example. The interface means 159, as well as the batteries or power supply can be put in a separate housing which might be fixed at a belt or packed in  
30 a pocket. It could also be sufficiently compact to be mounted on the HMD assembly.

1 Another embodiment of the present invention is illustrated in Figure 18. This  
simplified display assembly comprises a display panel 160 with three  
subregions of pixels 161 through 163. The number of subregions is limited  
to three for the sake of simplicity. The number of pixels in a subregion is  
5 also arbitrary in this example. It is to be noted that normally a display  
panel comprises hundreds or even more pixels. The scheme described on  
connection with Figure 18 can be easily adopted to larger display panels.  
The monolithically integrated LED array 158 of Figure 18 comprises three  
groups of one or more green diodes 165, 168, 171, three groups of one or  
10 more blue diodes 164, 166, 169, and three groups of one or more red diodes  
167, 170, 172. The array emits light through the substrate into the halfspace  
on the left hand side of the array. As an example the embodiment shown in  
Figure 17, has a green, red, and blue diode arranged in parallel and sharing  
one contact metallization, i.e. the green diode 171, red diode 170, and blue  
15 diode 169 are powered simultaneously by applying a voltage between the  
back contact and the contact 175. The diodes 172, 166, and 168 are powered  
simultaneously by applying a voltage between the back contact and the  
contact 176, and the diodes 164, 165, and 167 are powered simultaneously  
by applying a voltage between back contact and the contact 177. The  
20 interface means 174 now activates the diode array by rows so that at  $t = t_1$ ,  
the subregion 161 sees green light emitted by diode 171, the subregion 162  
sees red light emitted by diode 170, and the subregion 163 sees blue light  
emitted by diode 169. At  $t = t_2$ , the next row of diodes is activated and the  
subregion 161 sees red light emitted by diode 172, the subregion 162 sees  
25 blue light emitted by diode 166, and the subregion 163 sees green light  
emitted by diode 168. Next, the subregions see blue, red, and green,  
respectively. Then the whole process repeats. The interface means needs to  
be implemented such that the first pixel 161 receives green, then red, then  
blue, while the second pixel receives red, blue, green, and the third pixel  
30 blue, green, red. The key to this approach is to employ a monolithic  
multicolor diode array whose LEDs are smaller than a subregion size, as it  
is shown in Figure 18. The embodiment shown in Figure 18 has the  
advantage that it solves the problem of color flicker (discussed above)

1 present in display assemblies operating in FSC such as that shown in Figure  
17. By increasing the granularity of the color at one moment in time, rapid  
eye movements by the user will not produce the effect of two offset  
monochromatic bodies, rather two offset diffuse color bodies, which is the  
5 normal sensation when the eye changes orientation.

The present display assembly might comprise an infrared or RF receiver  
coupled to the interface means for driving the display panel and diodes.  
This allows wireless operation which is of particular importance in case of  
10 HMD.

The interface means might comprise a device for receiving input from a still  
image reproducer, video recorder, television tuner, CD-ROM, PC, a  
hand-held computer, and so forth. A HMD could in such a case be powered  
15 by the hand held computer directly, or in fact be a hand held computer.

The display assembly might in addition comprise a sensor for ambient light  
detection and a circuitry for automatic adaptation of the intensity of light  
emitted by the monolithic multicolor light source. This helps to improve the  
20 contrast in case of a HMD.

25

30

## CLAIMS

1. Light emitting diode array having a substrate (20) and a semiconducting layer (21) situated thereon, said array comprising at least two metal-insulator type light emitting diodes, whereby

- a first of said light emitting diodes comprises
  - a first active region ( $D_1$ ) which is compensated by a first group of impurities and has a first metal Schottky contact (24), and
  - a first conductive region (23.2) which has a first ohmic contact and is situated adjacent to said first active region ( $D_1$ ),
- a second of said light emitting diodes comprises
  - a second active region ( $D_2$ ) which is compensated by a second group of impurities and has a second metal Schottky contact (25), and
  - a conductive conductive region (23.3) which has a second ohmic contact and is situated adjacent to said second active region ( $D_2$ ),

said active regions ( $D_1$ ,  $D_2$ ) being formed by means of laterally varied impurity introduction into said semiconducting layer (21) such that - if a bias is applied between said ohmic metal contacts and Schottky contacts - electrical charges are injected from said ohmic metal contacts into said conductive regions and transported primarily parallel to the substrate plane from there into said first or second active regions leading to impurity-induced multicolor electroluminescence.

2. The array of claim 1, wherein said two light emitting diodes said first and second ohmic contacts are carried out as one common contact (23).
3. The array of claim 1, wherein said two light emitting diodes said first and second first metal Schottky contacts are carried out as one common contact.

- 1     4. The array of claim 1, wherein said conductive regions are intentionally  
doped to enhance their conductivity.
- 5     5. Light emitting diode array having a substrate (60) and a semiconducting  
layer (61) situated thereon, said array comprising at least two p-i-n type  
light emitting diodes, whereby
- a first of said light emitting diodes comprises at least a first active  
region ( $D_1$ ), compensated by a first group of impurities, surrounded  
on one side by an n-type conductive region (62a), and on the other  
side by a p-type conductive region (63a), each conductive region  
having an associated ohmic contact (64, 65), and
  - a second of said light emitting diodes comprises at least a second  
active region ( $D_2$ ), compensated by a second group of impurities,  
surrounded on one side by an n-type conductive region (62b), and  
on the other side by a p-type conductive region (63b), each  
conductive region having an associated ohmic contact (64, 68)
- said active regions ( $D_1$ ,  $D_2$ ) and conductive regions (62x, 63x) being  
formed by means of laterally varied impurity introduction into said  
semiconducting layer (61) such that - if a bias is applied to said  
contacts - electrical charges are injected into said conductive regions  
and transported primarily parallel to the substrate plane from there into  
said first or second active regions leading to impurity-induced  
multicolor electroluminescence.
- 25     6. The array of claim 5, wherein either the ohmic contacts to said p-type  
conductive regions or the ohmic contacts to said n-type conductive  
regions are carried out as one common contact (64).
- 30     7. The array of any of the preceding claims, in which independent rows of  
light emitting diodes are defined by electrical isolation (26; 70).
8. The array of claim 1 or 5, comprising  $(\text{Ga}_{1-x}\text{Al}_x)_{1-y}\text{In}_y\text{N}$ .

- 1 9. The array of claim 1 or 5, wherein different local doping conditions are obtained by means of different choices of the dopants and/or their local concentrations and/or the doping processes.
- 5 10. The array of claim 1 or 5, wherein the light of the light emitting diodes is partially radiated into at least one of the half spaces above or below the substrate.
- 10 11. The array of claim 1 or 5, wherein said substrate is conductive and serves as a common electrode of at least two of said light emitting diodes.
- 15 12. The array of claim 1 or 5, wherein said first and second groups of impurities are chosen such that said first light emitting diode emits light of a first of the three primary colors and the second light emitting diodes emits light of a second of the three primary colors.
- 20 13. The array of claim 1, 5, or 12, comprising a discrete light emitting diode, preferably an AlGaAs light emitting diode emitting red light.
- 25 14. Semiconductor lamp for illumination of a light modulating display panel which comprises pixels which can be individually activated for generation of an image by means of light modulation, said lamp being characterized in that it comprises at least two monolithically integrated light emitting diodes, whereby
- a first of said light emitting diodes comprises a first active region ( $D_1$ ) which is compensated by a first group of impurities, and
  - a second of said light emitting diodes comprises a second active region ( $D_2$ ) which is compensated by a second group of impurities,
- 30 said lamp further comprising means for driving said two light emitting diodes such that they emit light in a fast, alternating manner by applying bias pulses to said light emitting diodes such that electrical charges are transported into said active region of said first light

- 1 emitting diode and said active region of said second light emitting  
diode in an alternating manner, the electrical charges transported into  
said first active region causing light of a first color to be emitted, and  
the electrical charges transported into said second active region  
5 causing light of a second color to be emitted.
15. The lamp of claim 14, wherein the frequency of said bias pulses is  
chosen such that the change in color is barely perceivable.
- 10 16. The lamp of claim 15, wherein said first color is green, said second  
color is blue.
17. The lamp of claim 16, comprising a third light emitting diode which  
emits red light.
- 15 18. The lamp of claim 17, wherein the light emitting diodes emitting light of  
a first color (156) are electrically wired in parallel, the light emitting  
diodes emitting light of a second color (155) are electrically wired in  
parallel, and the light emitting diodes emitting light of a third color (157)  
20 are electrically wired in parallel.
19. The array of claim 18, or 17, comprising a discrete light emitting diode,  
preferably an AlGaAs light emitting diode emitting red light.
- 25 20. The lamp of claim 17, wherein at least two groups of light emitting  
diodes are formed and provided with wiring (175, 176, 177) such that the  
first group and second group emit light in an alternating manner, each  
of said groups comprising a light emitting diode emitting light of a first  
color (171) a light emitting diode emitting light of a second color (170),  
30 and a light emitting diode emitting light of a third color (169).
21. Display assembly comprising an array or lamp according to any of the  
preceding claims.

- 1     22. The display assembly of claim 21, comprising a light modulating display panel being arranged such that it is evenly illuminated by said light emitting diodes.
- 5     23. The display assembly of claim 21, comprising optical elements such as mirrors, lenses, prisms, gratings, total internal reflectors, or fibers.
- 10    24. The display assembly of any of the claims 21, 22, or claim 23 being integrated into the frame of a head-mounted display, or camera view finder.
- 15    25. The display assembly of claim 22 in combination with claim 20, wherein said first group illuminates a first subregion of said display panel (150) and said second group a second subregion thereof in order to avoid color flicker and to improve efficiency by eliminating the generation of unneeded light.
- 20    26. The display assembly of claim 21, further comprising control electronics (159; 174) for controlling the bias pulses applied to said light emitting diodes and thus their light intensity, said control electronics further comprising an input (153; 173) for receiving image data to be displayed.
- 25    27. The display assembly of claim 26 in combination with claim 22 comprising means for driving and synchronizing the pixels of said light modulating display panel.
- 30    28. The display assembly of claim 27, wherein said means for driving has power saving means which ensure that unneeded light emitting diodes in sub-areas are not activated.

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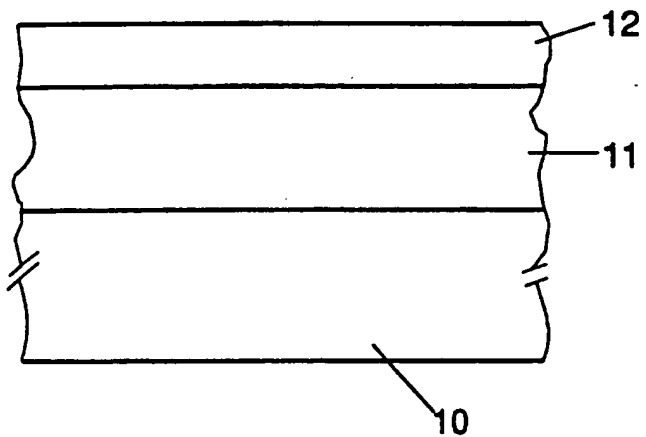


FIG. 1A

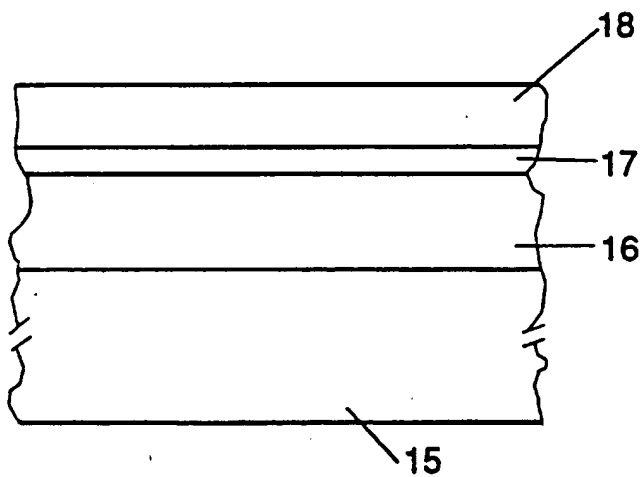


FIG. 1B

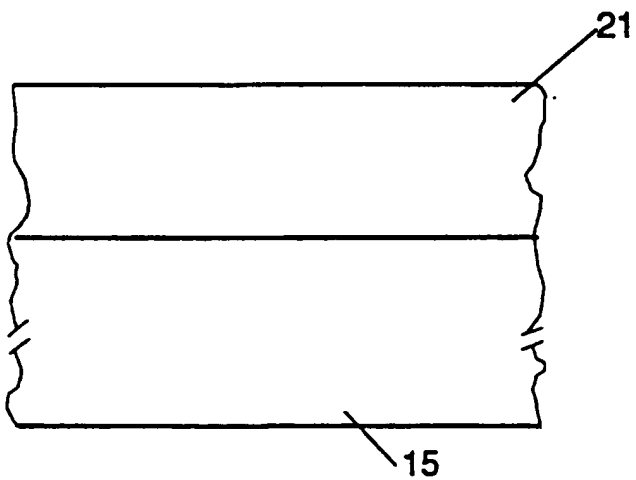


FIG. 1C

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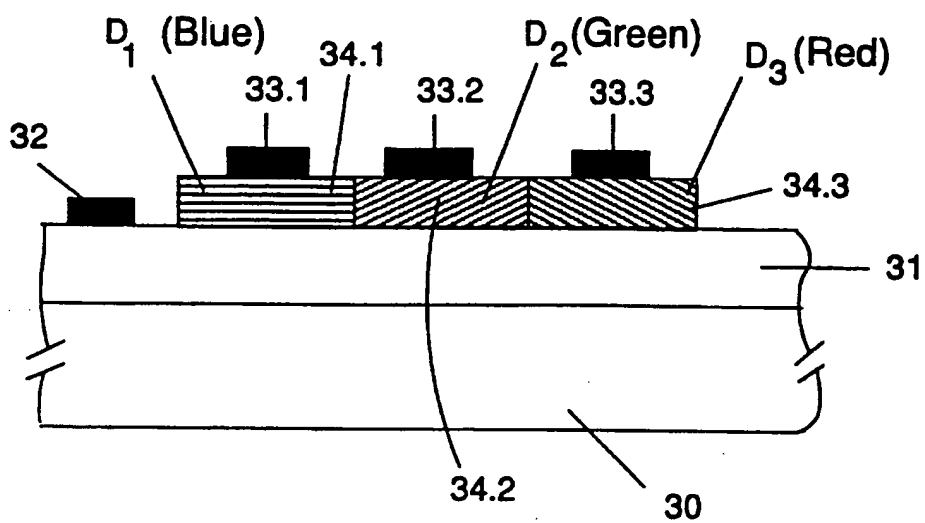


FIG. 2A

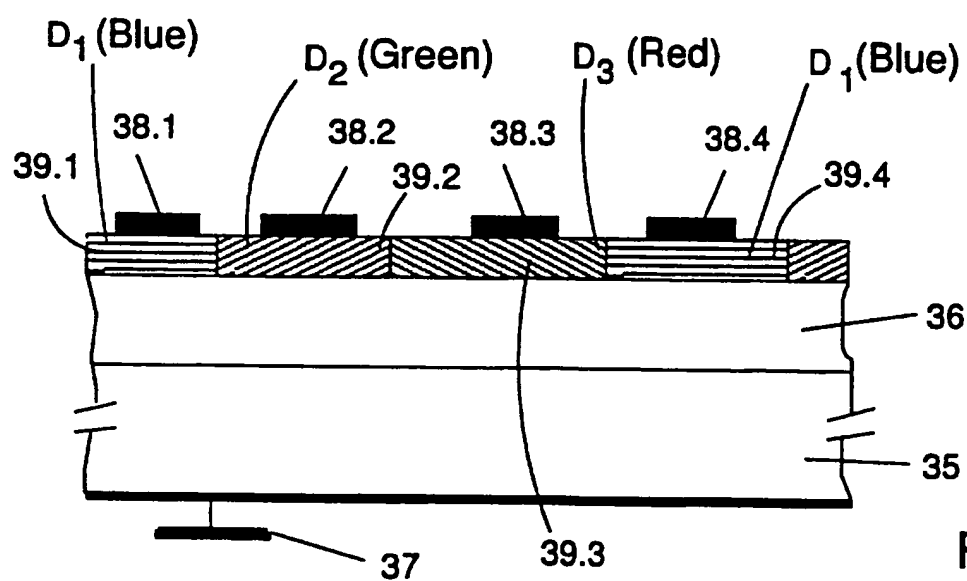
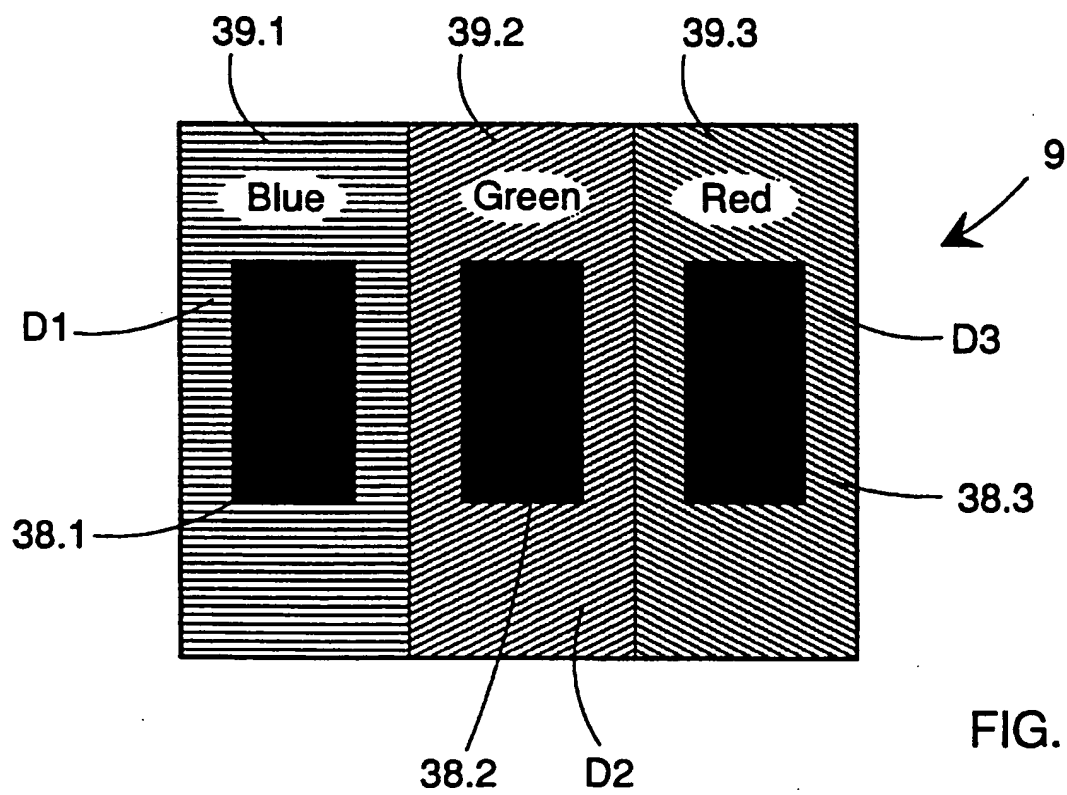
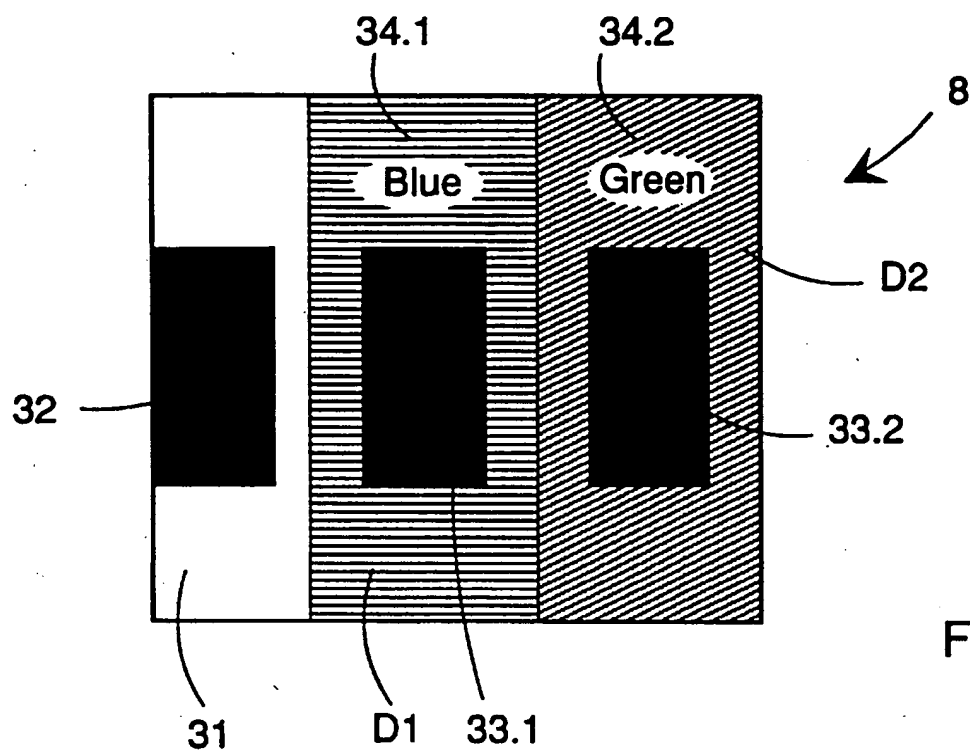


FIG. 2B

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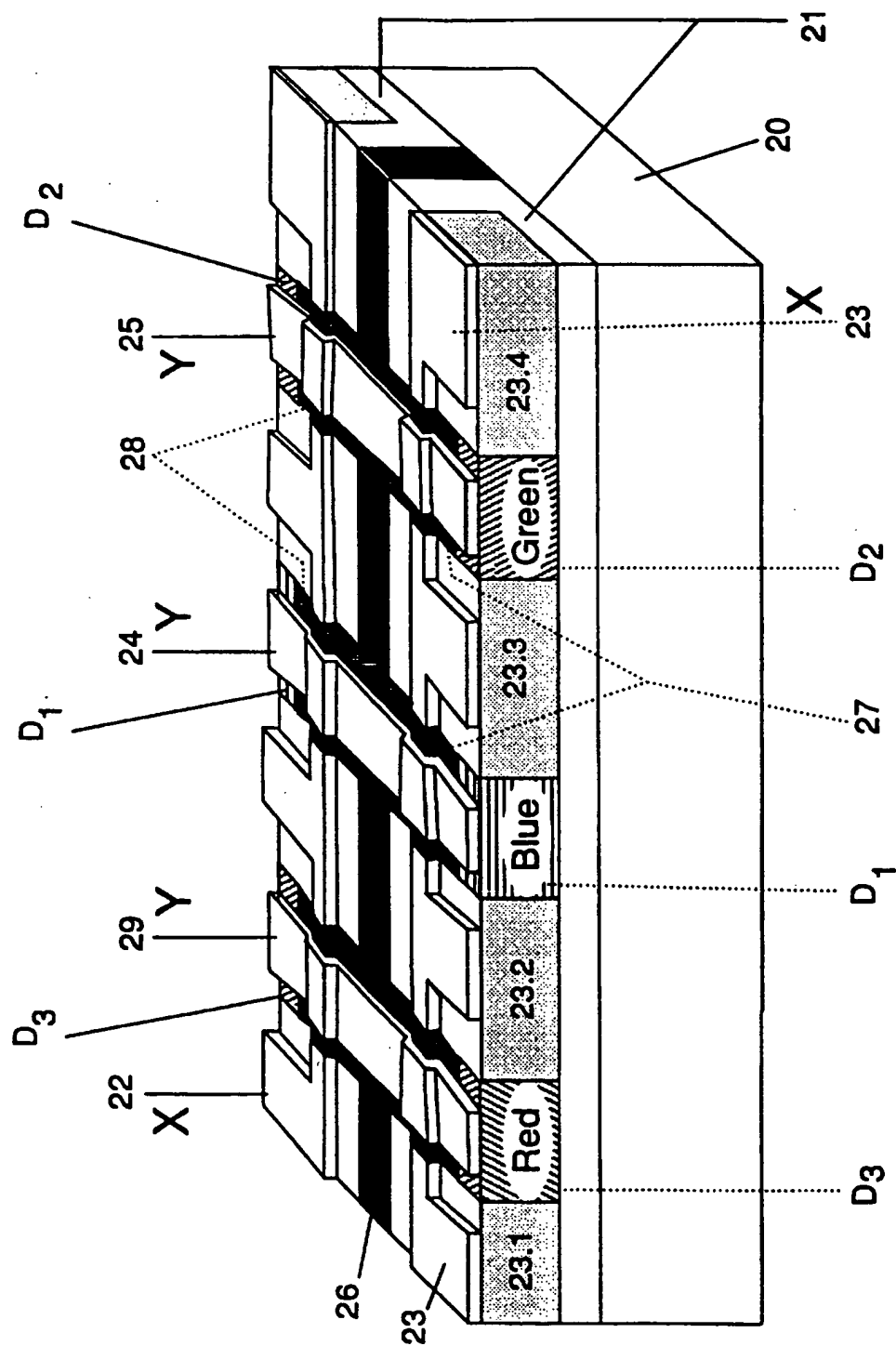


FIG. 3

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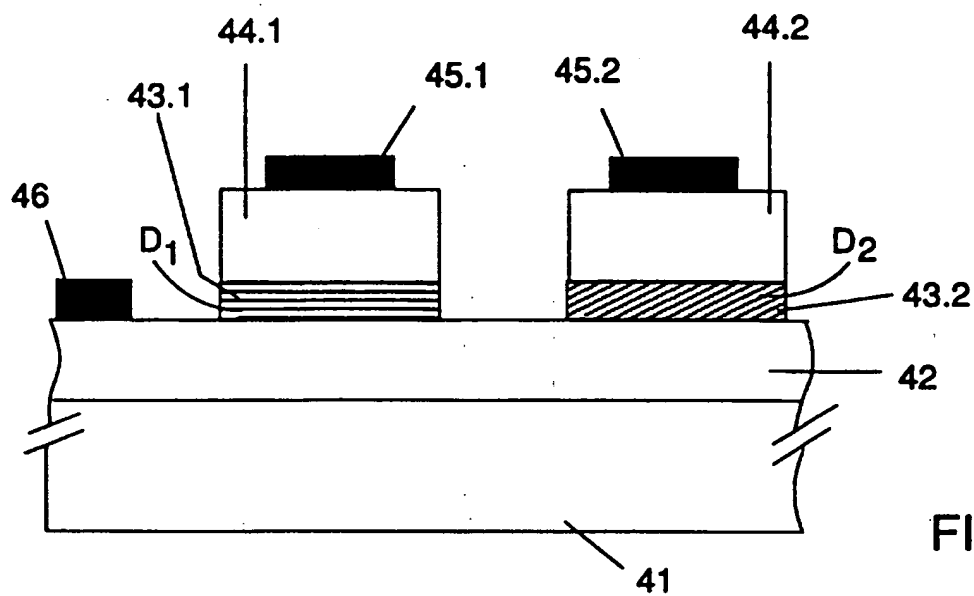


FIG. 4A

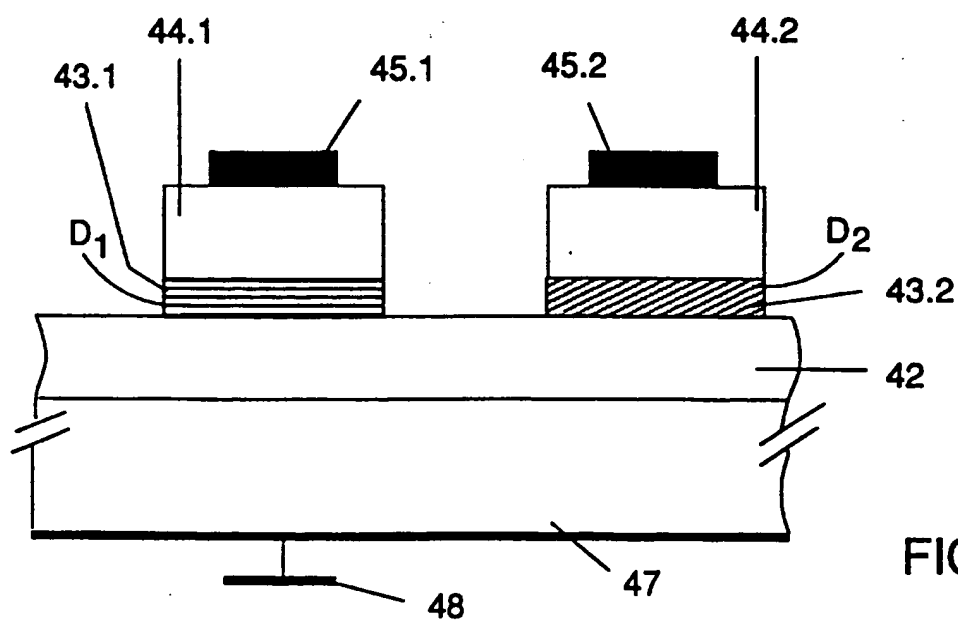


FIG. 4B

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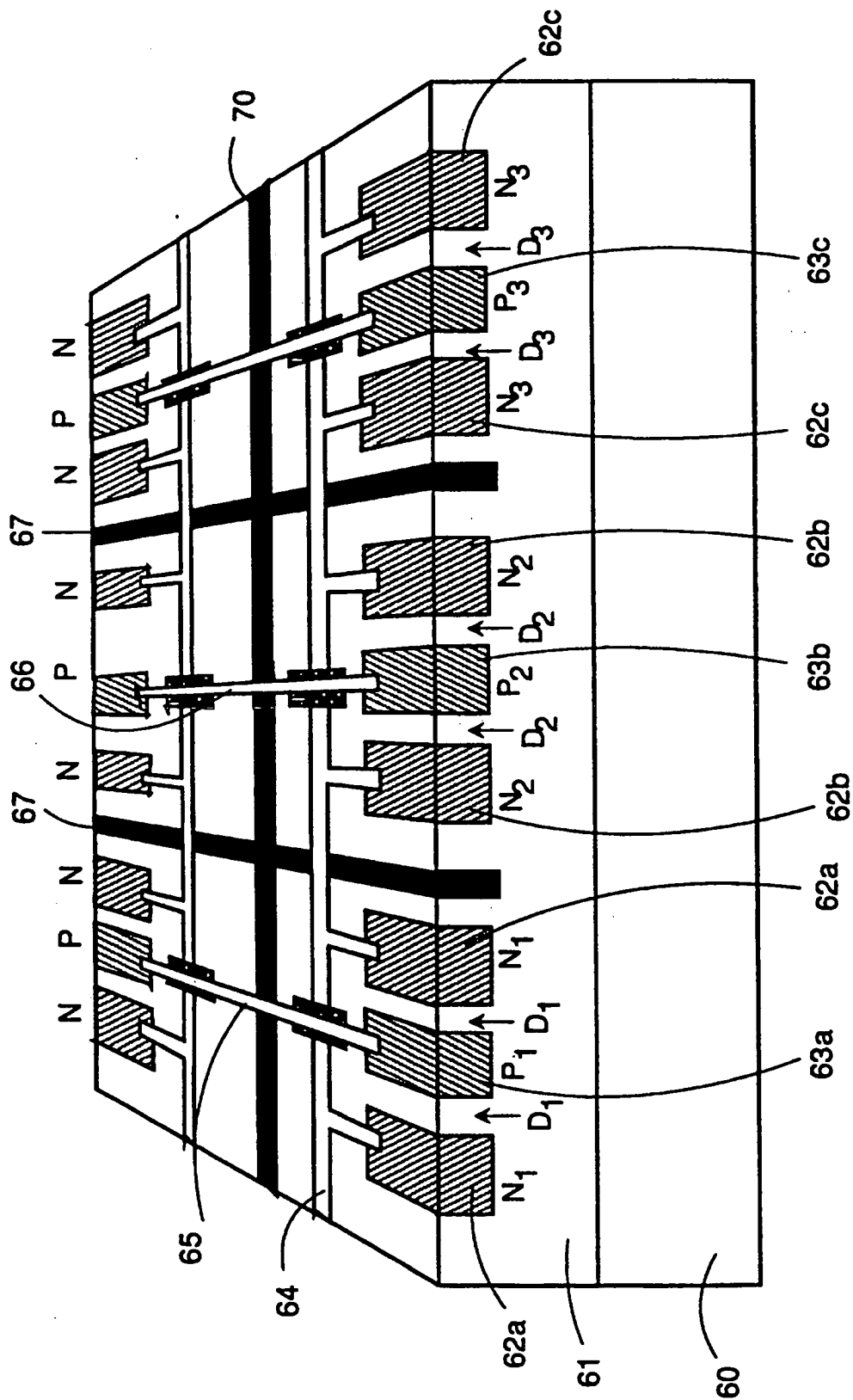
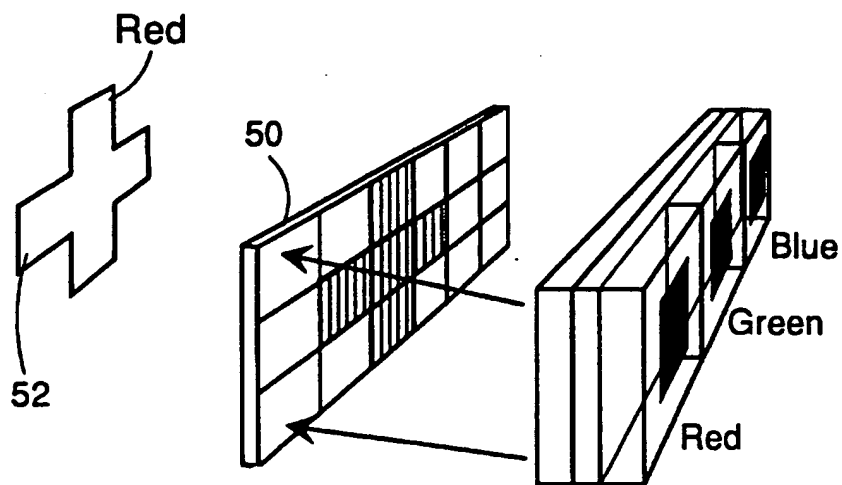
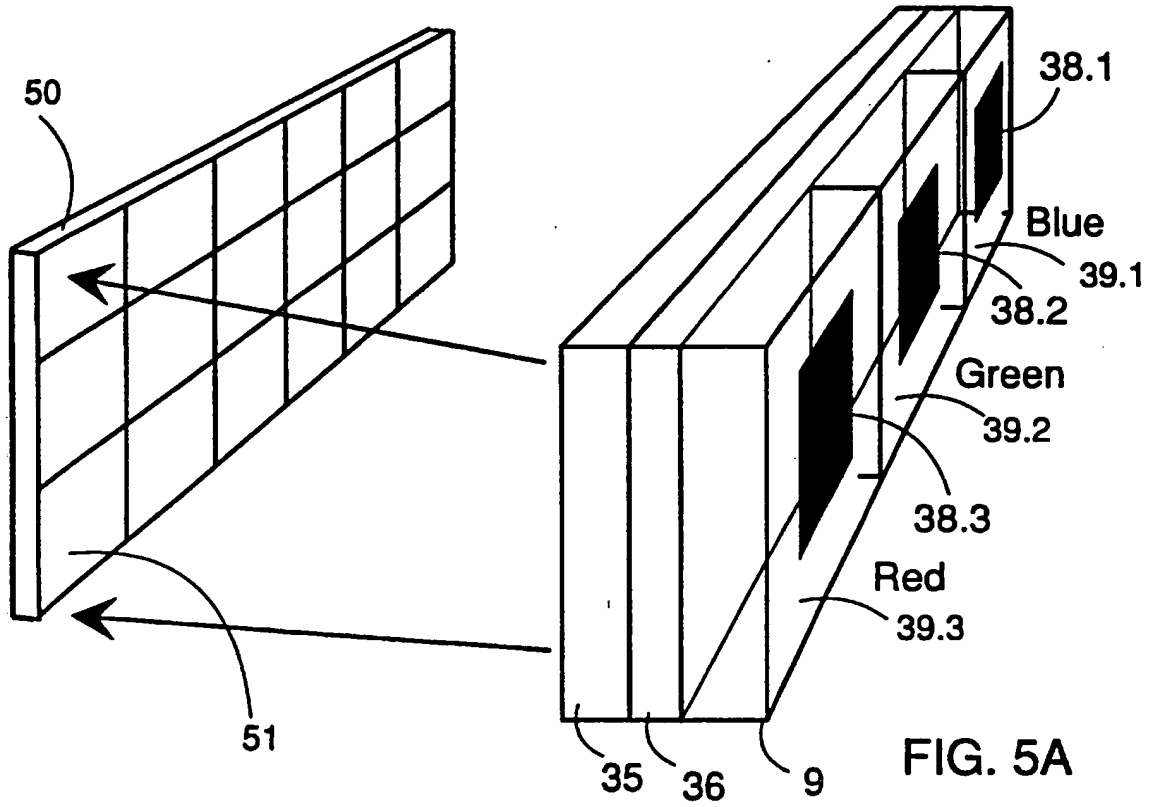


FIG. 4C

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$t=t_1$

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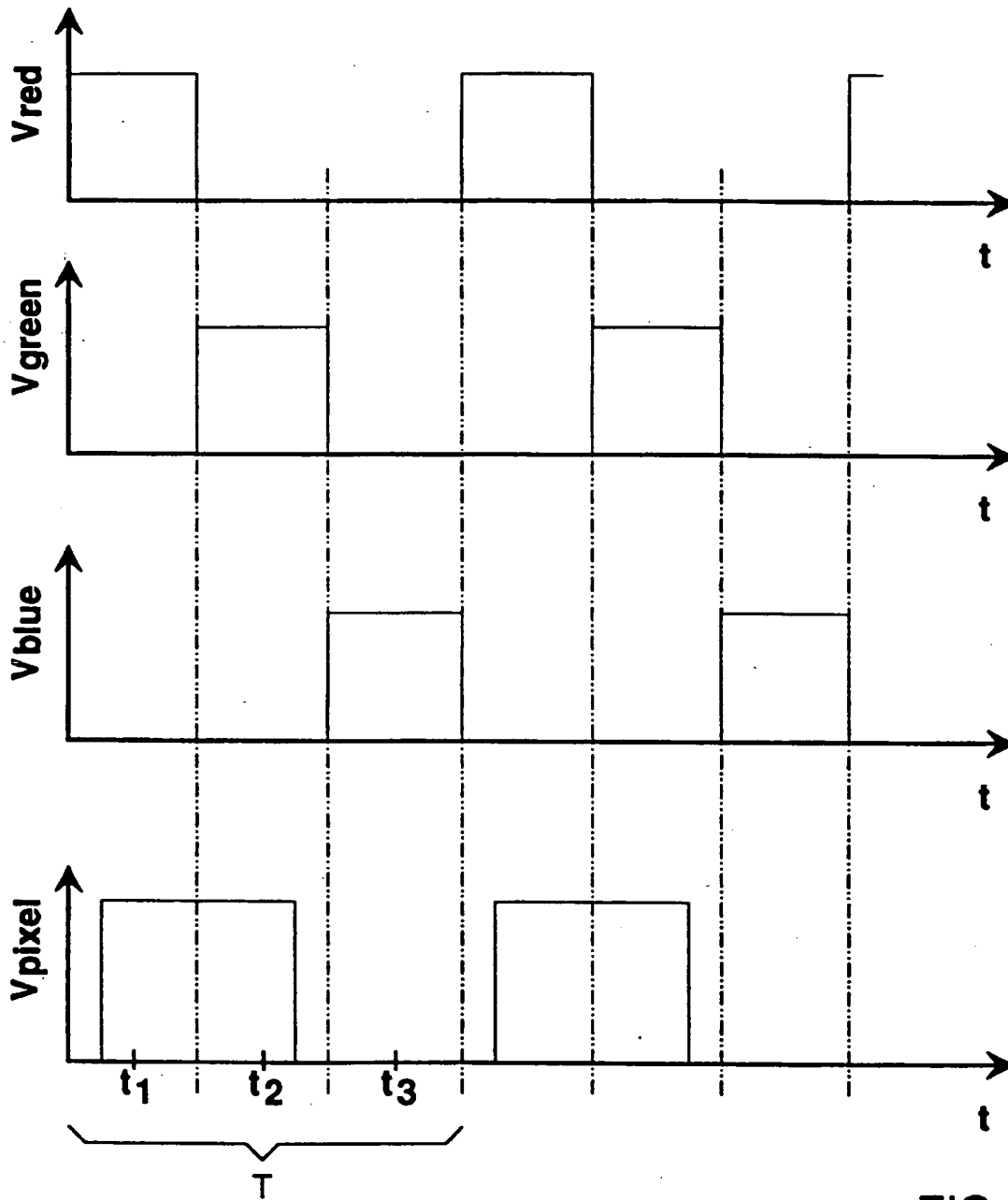


FIG. 6

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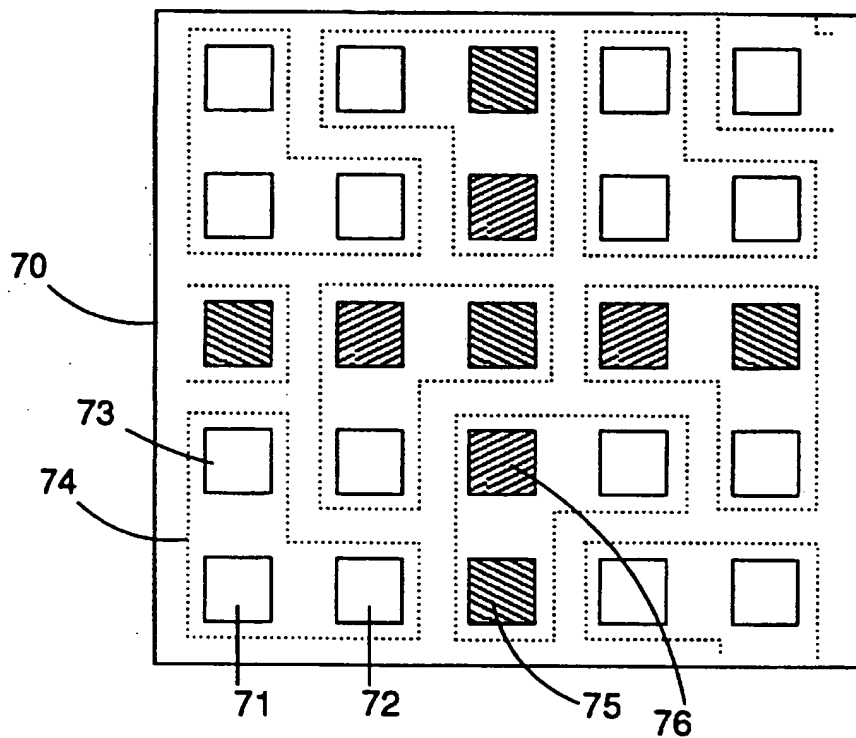


FIG. 7

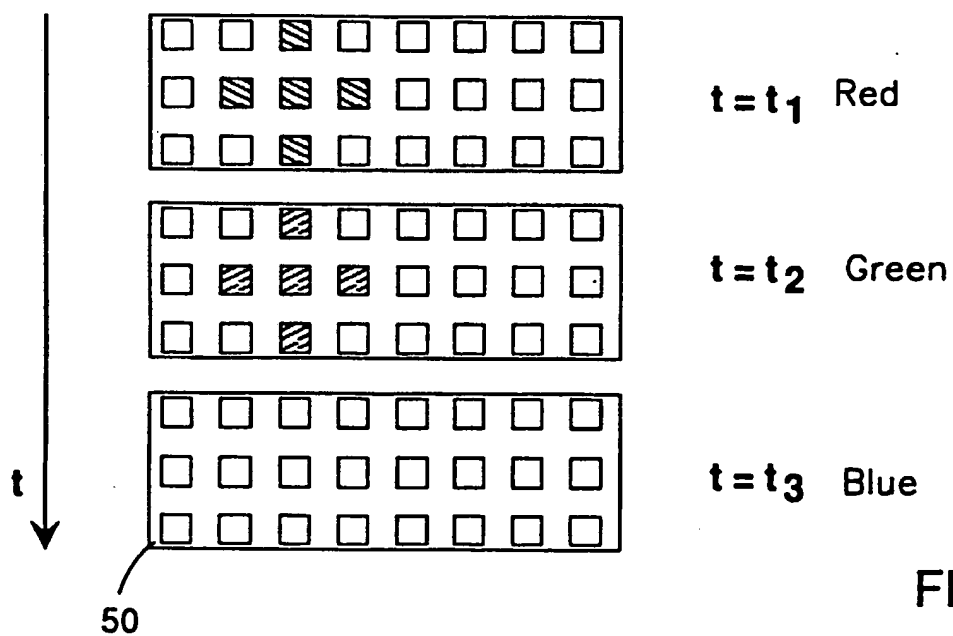
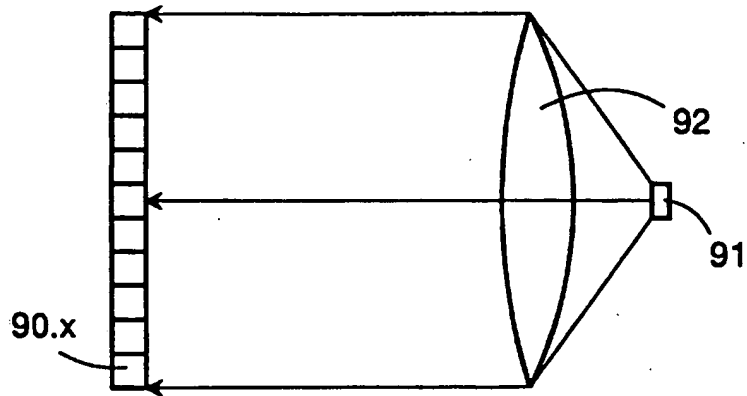
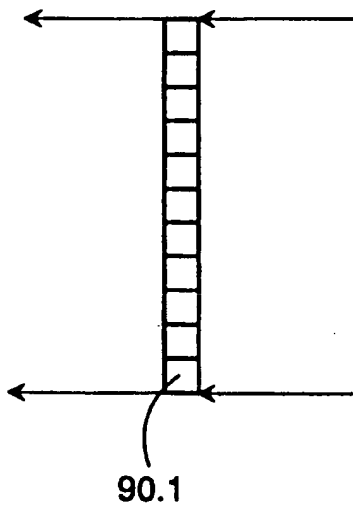


FIG. 8

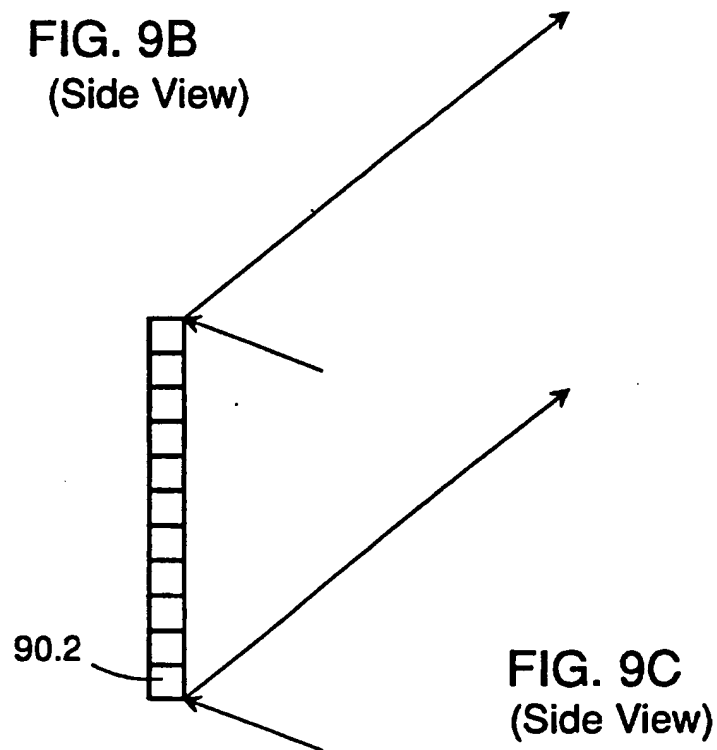
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**FIG. 9A**  
(Top View)



**FIG. 9B**  
(Side View)



**FIG. 9C**  
(Side View)

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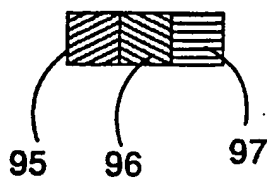


FIG. 10A

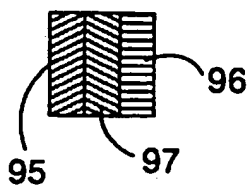


FIG. 10B

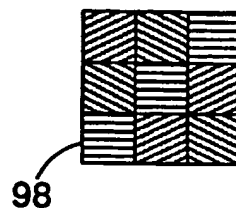


FIG. 10C

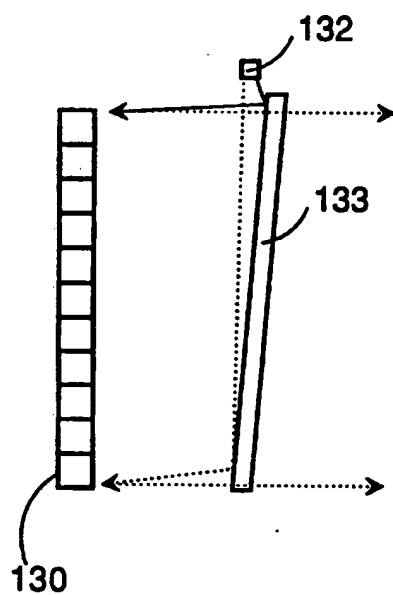


FIG. 11  
(Top View)

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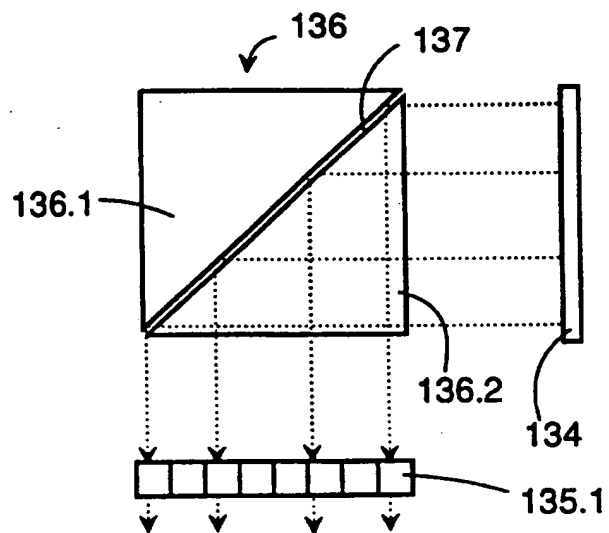


FIG. 12A  
(Top View)

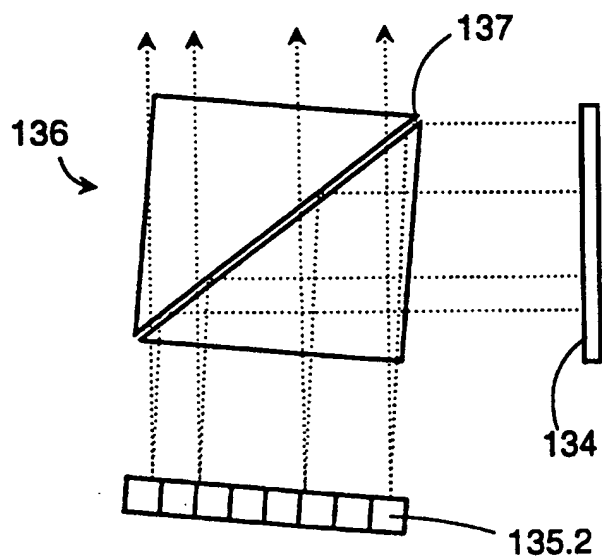


FIG. 12B  
(Top View)

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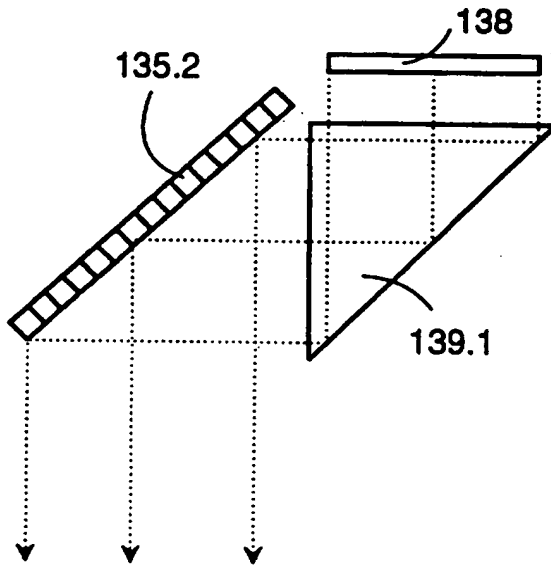


FIG. 12C  
(Top View)

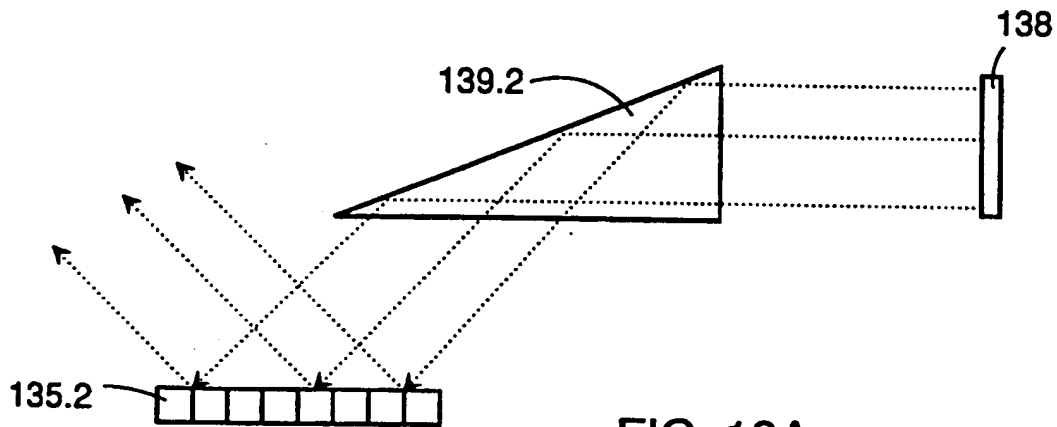
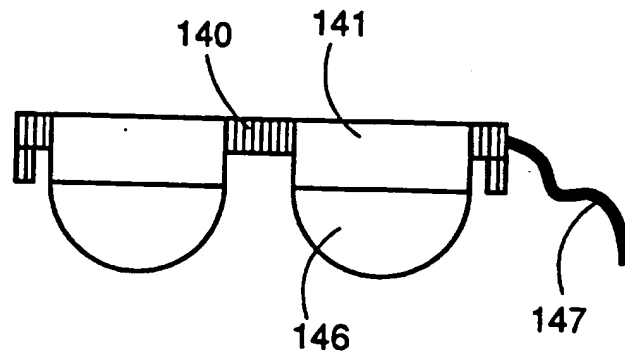
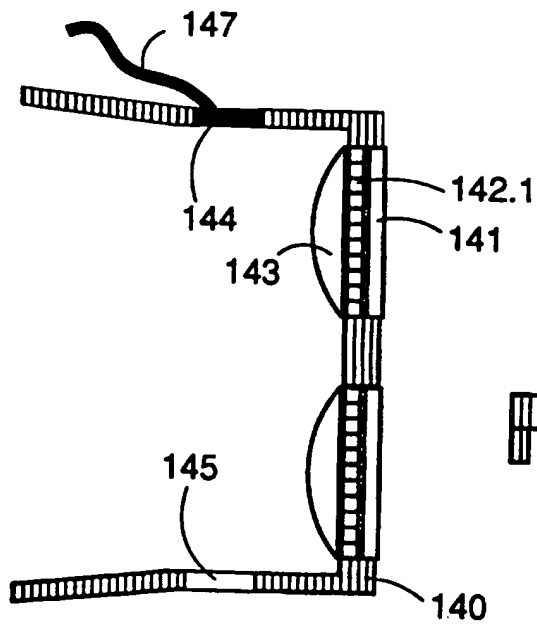
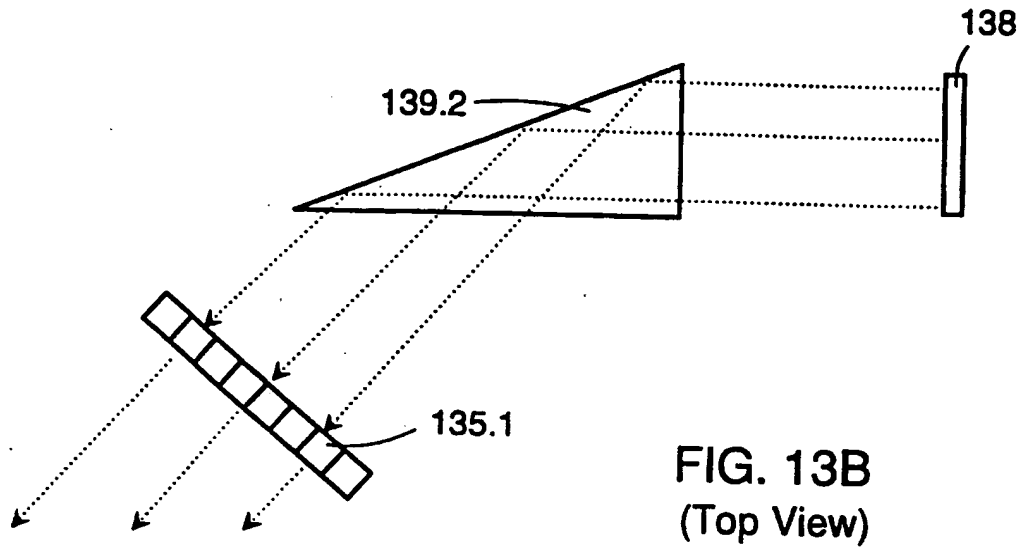


FIG. 13A  
(Top View)

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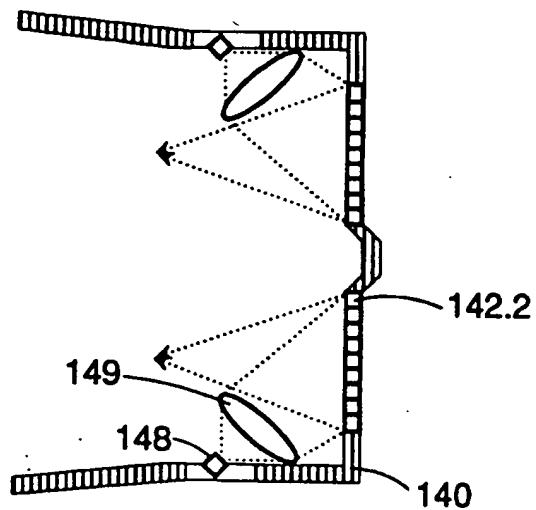


FIG. 15  
(Top View)

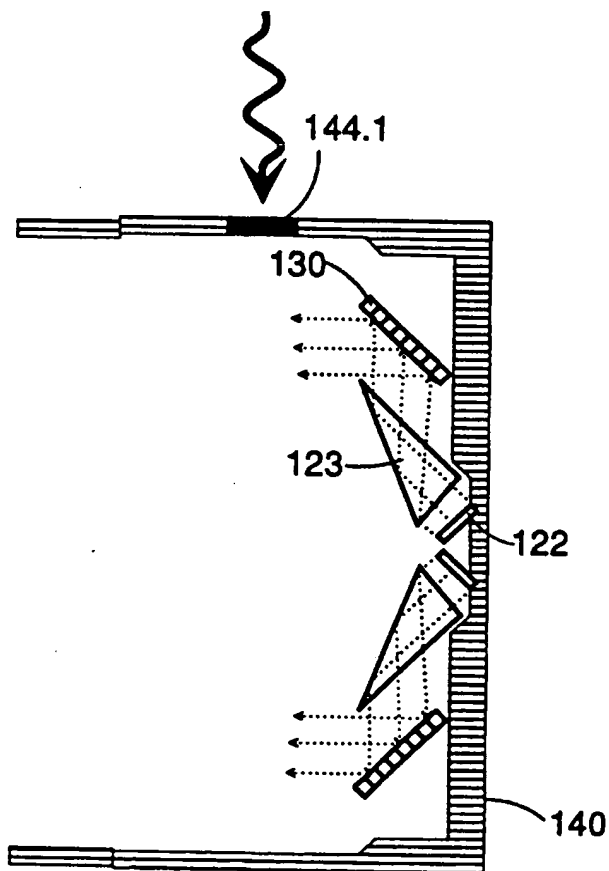


FIG. 16  
(Top View)

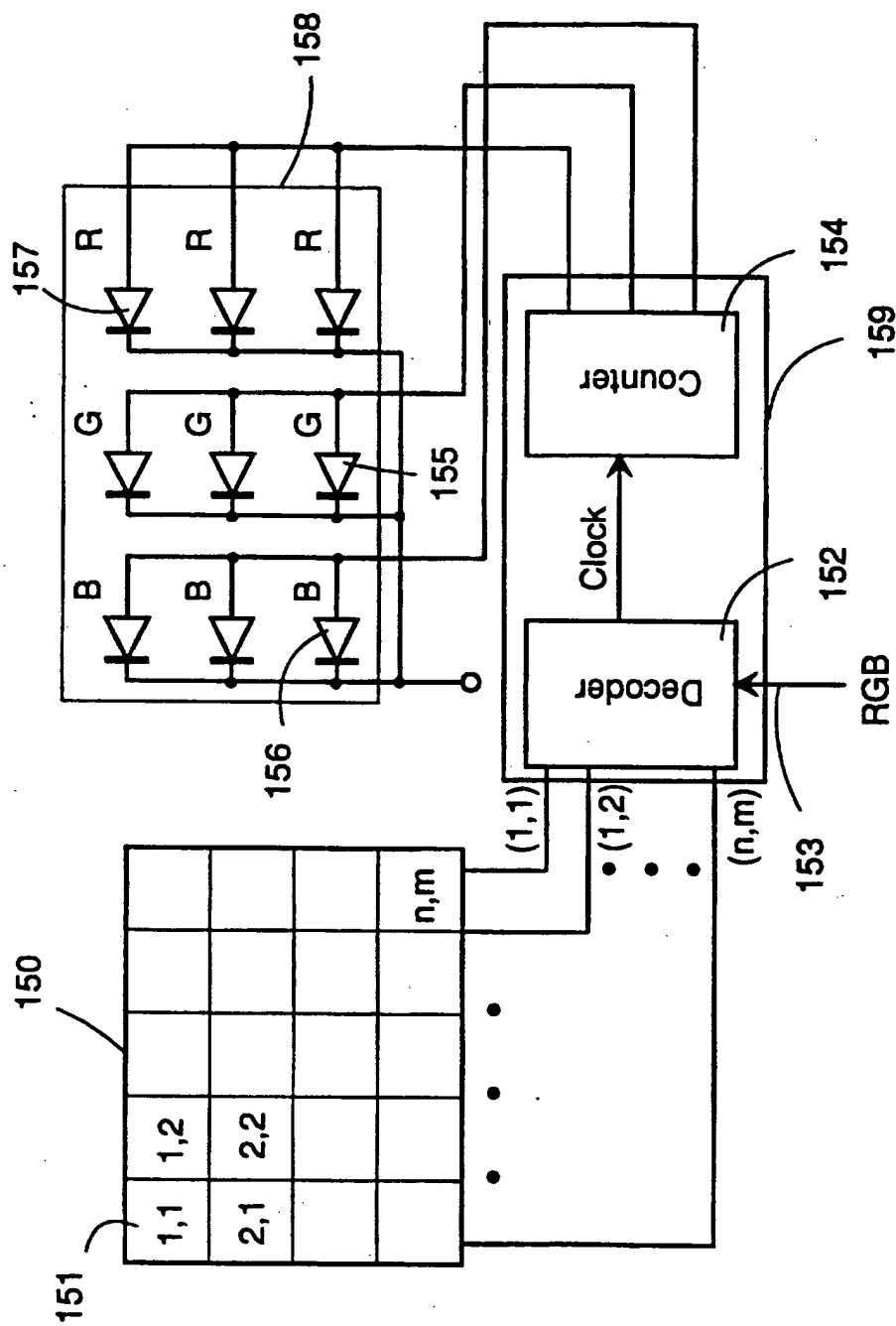
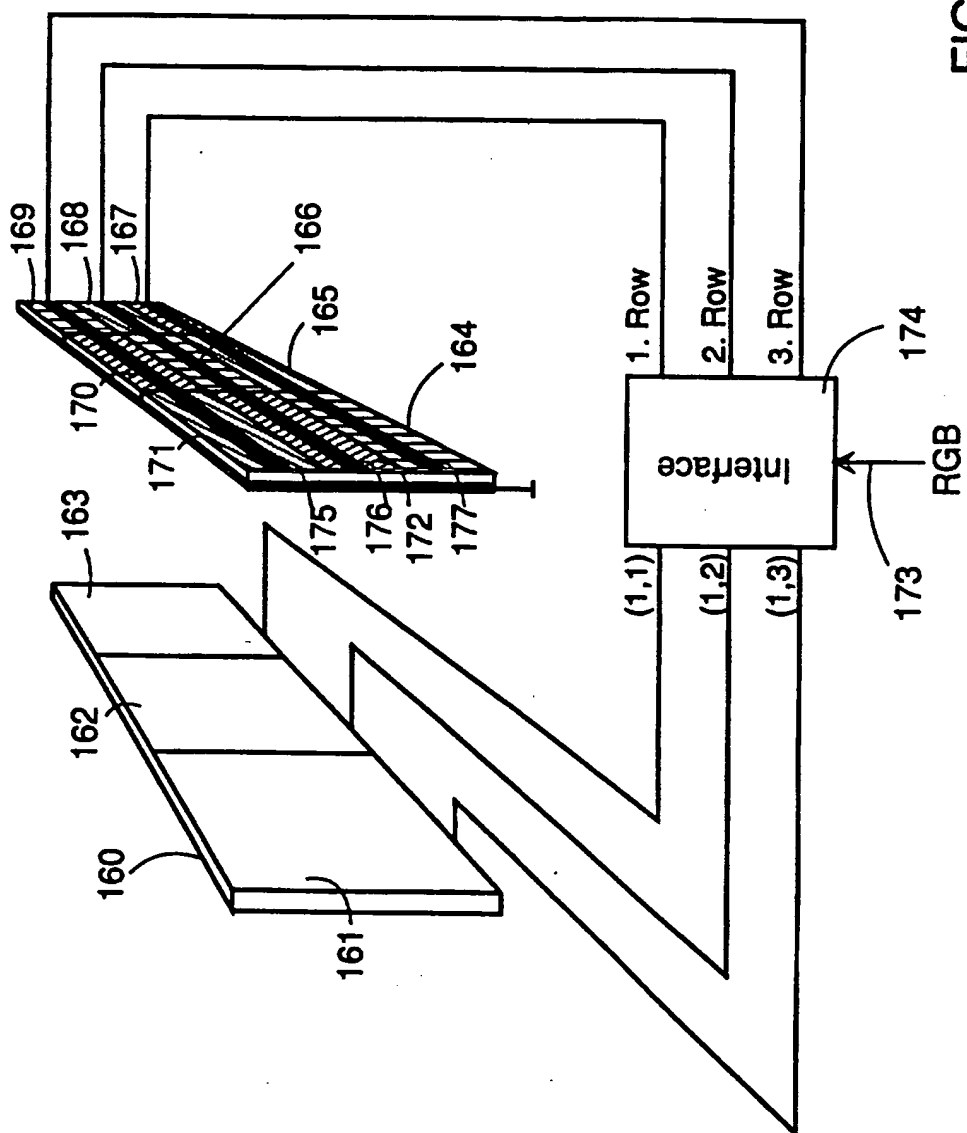


FIG. 17



# INTERNATIONAL SEARCH REPORT

International Application No  
PCT/IB 95/00367

A. CLASSIFICATION OF SUBJECT MATTER  
IPC 6 H01L27/15 G09G3/34

According to International Patent Classification (IPC) or to both national classification and IPC

## B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

IPC 6 H01L G09G

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

## C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	EP-A-0 351 867 (SHARP KK) 24 January 1990  see column 4, line 35 - column 5, line 25 see column 9, line 36 - column 10, line 16; figures 11,12	14-17, 19, 21-23, 26,27
A	---	1,5,12
A	US-A-5 273 933 (HATANO AKO ET AL) 28 December 1993 see column 4, line 36 - line 43; figure 4 ---	1,8
A	GB-A-2 263 185 (SAMSUNG ELECTRON DEVICES CO. LTD) 14 July 1993 see the whole document ---	14
	--- -/--	

☒ Further documents are listed in the continuation of box C.

☒ Patent family members are listed in annex.

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Date of the actual completion of the international search

25 July 1995

Date of mailing of the international search report

04.08.95

Name and mailing address of the ISA

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De Laere, A

# INTERNATIONAL SEARCH REPORT

International Application No  
PCT/IB 95/00367

## C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
P,Y	<p>US-A-5 359 345 (HUNTER C ERIC) 25 October 1994</p> <p>see column 4, line 35 - column 5, line 25 see column 9, line 36 - column 10, line 16; figures 11,12 -----</p>	<p>14-17, 19, 21-23, 26,27</p>

# INTERNATIONAL SEARCH REPORT

Information on patent family members

International Application No

PCT/IB 95/00367

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		DE-T- 68919291	23-03-95
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